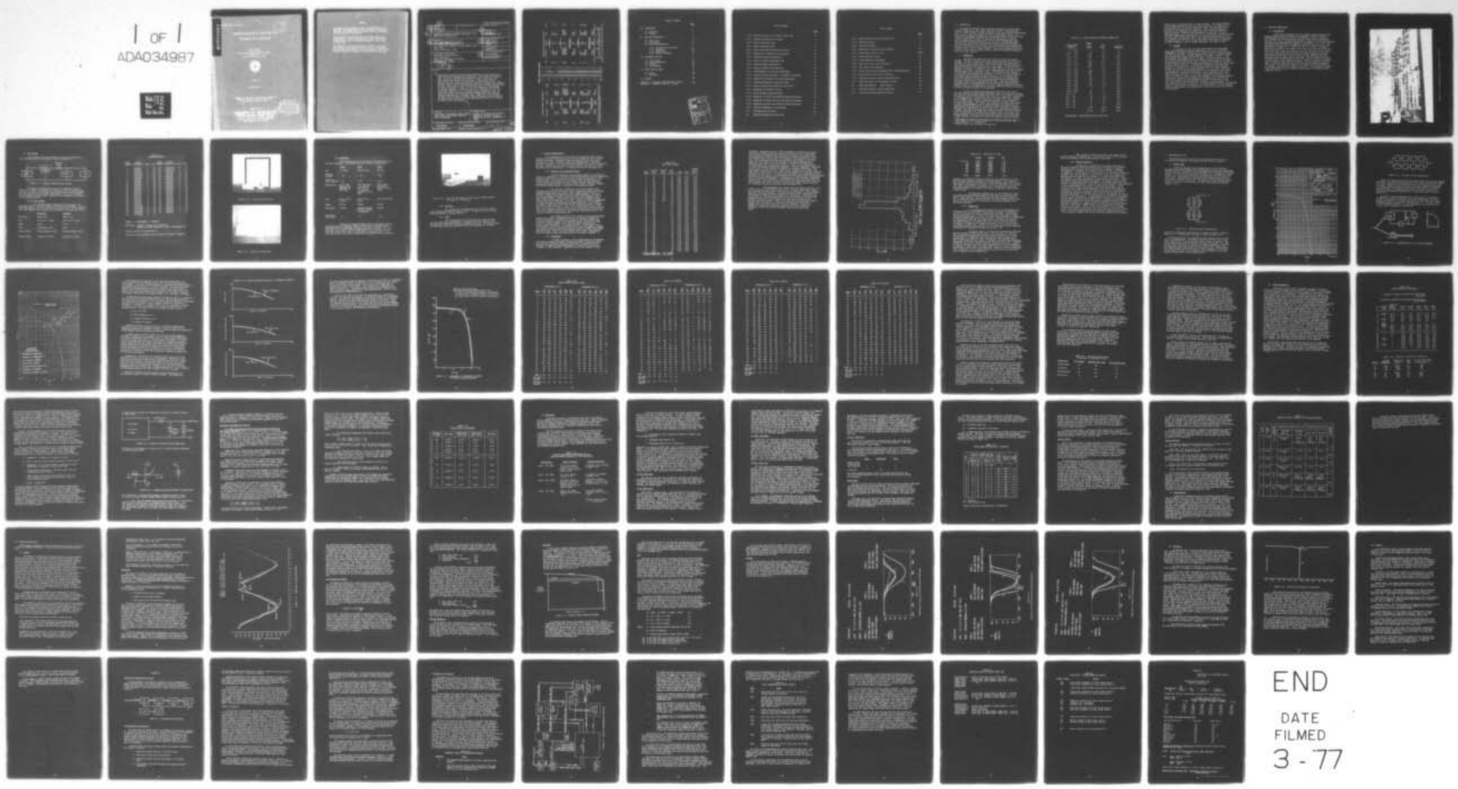
AD-A034 987 COAST GUARD RESEARCH AND DEVELOPMENT CENTER GROTON CONN F/G 10/2
LABORATORY EVALUATION OF SOLAR POWER UNITS FOR MARINE AIDS TO N--ETC(U)
JUN 76 J S RYBA, D A NAUS

UNCLASSIFIED CGR/DC-5/76 USCG-D-106-76 NL

1 OF 1
ADA034987



END
DATE
FILMED
3-77

USCG [illegible]

Avery Point

Groton, Connecticut 06340

June 1976

Interim Report

Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

NOTICE

Technical Report Documentation Page

19

18

1. Report No.
USCG-D-106-76

2. Government Accession No.

3. Recipient's Catalog No.

6

4. Title and Subtitle
LABORATORY EVALUATION OF SOLAR POWER UNITS FOR MARINE AIDS TO NAVIGATION.

11

5. Report Date
June 1976

6. Performing Organization Code

10

7. Author's)
John S. Ryba and David A. Naus

14

8. Performing Organization Report No.
CGR&DC-5/76

9. Performing Organization Name and Address
U. S. Coast Guard Research and Development Center
Avery Point
Groton, Connecticut 06340

10. Work Unit No. (TRAIS)
762510

11. Contract or Grant No.
762511.02/1

13. Type of Report and Period Covered

9

Interim Report,

12. Sponsoring Agency Name and Address
Department of Transportation
U. S. Coast Guard
Office of Research and Development
Washington, DC 20590

14. Sponsoring Agency Code

15. Supplementary Notes

12 79p.

16. Abstract

This report describes the Coast Guard evaluation of solar energy as a power source for lighted aids to navigation. Fifty-three solar powered aids, on test in a natural environment at Groton, Connecticut, have been continuously monitored for two years. Solar arrays from two manufacturers were tested with neither being wholly satisfactory. One had major quality control problems while the other suffered from inadequate sealing. Three types of lead-acid batteries used for energy storage have all been satisfactory to date. The test has indicated the advantages of voltage regulation in reducing water use in batteries, but has not proved that regulation is in fact required for long battery life. The insolation measured has shown excellent agreement with that predicted using the averages from a surrogate area. Almost all of the original estimates that were made to predict system performance (battery capacity vs. time of year) proved to be very conservative and most of the systems performed better than expected.

17. Key Words
solar power, solar panels, solar arrays, photovoltaic, insolation, batteries, aids to navigation

18. Distribution Statement
Document is available to the public through the National Technical Information Service, Springfield, VA 22161
5

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	80	

1B

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

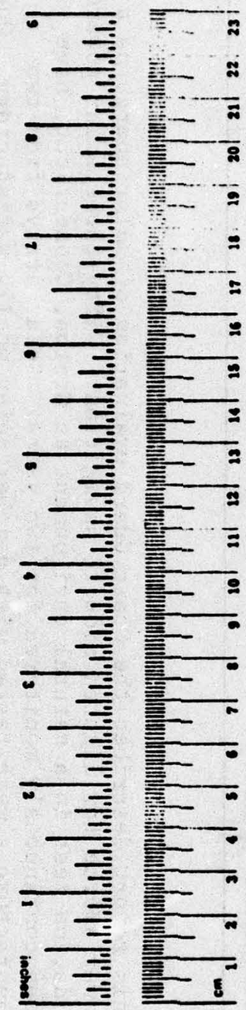
408 730

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

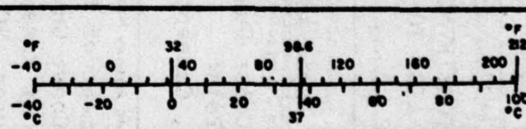


TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The United States Coast Guard maintains approximately 14,000 lighted aids to navigation, of which about 4,000 are on buoys. These aids are presently being powered by primary batteries of the zinc-carbon air-depolarized type. In 1971, the Coast Guard, faced with rising battery costs, and environmental problems of disposal of the used batteries, started a research program to investigate alternate low-power energy sources. A survey of the lighted aids, as shown in Table 1.0-1, indicated the power that would be required from any new source would be low. Preliminary study indicated that photovoltaic devices were the most promising candidates but that wind and wave generators and fuel cells should also be considered. Research was started in all of these areas but the Coast Guard applied the greatest effort to solar powered systems. This report describes the results to date, of the portion of solar research entitled "Laboratory Testing of Solar Cell Power Supplies."

1.1 Background

The first buoy lighted by electricity was in New York Harbor in 1888. The source of power, which was a cable from shore, did not prove reliable. In 1910, lighted buoys using acetylene gas were brought into use and were used for many years. About 1935, battery powered lights came into use and started replacing some of the gas lights. In 1950, it was decided to electrify all buoys/aids but it was 1968 before the last acetylene buoy/aid was retired. Initially, large (1,000 amp-hour) lead-acid storage batteries were used as the power source. These batteries were removed to shore depots for recharge when required. In 1962, the next change-over was started, from secondary to primary batteries. It was reasoned that the primary batteries would save money since the battery charging shops could be eliminated, and because the spent batteries would be dumped in the ocean, there would be less handling problems. The latter advantage disappeared when it was determined that the zinc-carbon air-depolarized batteries were not biodegradable and could no longer be dumped in the ocean. Besides having to be carried back to the base, additional costs were incurred in order to properly dispose of the batteries.

In 1971, the Coast Guard knew very little about solar power. The Coast Guard Field Testing and Development Center at Curtis Bay, Maryland, had conducted some limited testing with solar cells in the 1960's but because of high costs and poor reliability, that effort was terminated[1]. However, it now appeared that, because of advances in silicon solar arrays brought about by NASA's space program, solar power possessed a large potential as a new power source. As a result of a request for proposal (RFP) placed by Coast Guard Headquarters, solar powered systems were proposed by two companies; Heliotek/Spectrolab, a division of Textron, Sylmar, California, and Centralab Semiconductor, El Monte, California. Though each company designed to the same requirements as stated in the RFP, Spectrolab proposed a system consisting of an array with a nominal[2] output of 12 watts at 12 volts, 40 amp-hours of lead-acid battery capacity and a solid-state shunt voltage regulator, while the Centralab system consisted of an array with a nominal output of 20 watts at 12 volts, 120 amp-hour lead-acid battery

---

1 Final Report on Study of Solar Energy Use in Marine Navigation Aids, Reed Research, Inc., October 1972.

2 Nominal output is at 100 mW/cm^2, AM1 and 25°C.

TABLE 1.0-1. POWER REQUIRED TO OPERATE LIGHTED AIDS

AVERAGE POWER (WATTS)	NUMBER OF LIGHTS	% OF TOTAL	% CUMULATIVE
0 - 0.25	6	0.1	0.1
0.25 - 0.50	162	1.4	1.5
0.51 - 0.75	4,527	39.3	40.8
0.76 - 1.00	375	3.3	44.1
1.01 - 1.25	1,334	11.6	55.7
1.26 - 1.50	396	3.4	49.1
1.51 - 1.75	1,307	11.3	70.5
1.76 - 2.00	32	0.3	70.8
2.01 - 3.00	1,083	9.4	80.2
3.01 - 4.00	855	7.4	87.6
4.01 - 5.00	250	2.2	89.8
5.01 - 6.00	241	2.1	91.9
6.01 - 7.00	292	2.5	94.4
7.01 - 8.00	101	0.9	95.3
8.01 - 9.00	0	0	95.3
9.01 - 10.00	150	1.3	96.6
10.01 - 15	169	1.5	98.1
15.1 - 20	42	0.3	98.4
20.1 - 25	99	0.8	99.2
25.1 - 30	21	0.2	99.4
30.1 - 35	0	0	99.4
35.1 - 40	84	0.6	100.0
	11,526	100.0	100.0

Average Power = Instantaneous Power x Duty Cycle

capacity and a solid-state series voltage regulator. The large difference in the designs resulted from an incomplete knowledge of the magnitude of the variables that would affect system operations, and from selection of different safety factors by the companies. These proposed systems were procured and the companies were given contracts to test the systems at their own plants. To obtain more knowledge, it was decided to acquire additional systems and to operate them in our own facility. For this purpose, 34 solar powered systems were ordered, by Coast Guard Headquarters, from each company in the spring of 1972. Each system consisted of a solar array, a storage battery, and a box to house the battery and required wiring and any other components, such as voltage regulators, that might be added.

1.2 Program

In the fall of 1972, the Coast Guard Research and Development Center was established at Groton, Connecticut, and in one of its first assignments, the Center was directed to evaluate the solar powered systems that had been acquired. The goal appeared quite simple - determine whether these systems will operate satisfactorily for a number of years. It was soon apparent that things were not so simple. The real need was to find out if solar energy systems were cost effective substitutes for the primary batteries which are the current source of power, and in order to do this we would need to know how to optimize system design and what the most probable causes of failure would be. A "laboratory evaluation" could help reach that goal by research into actual long-term operation of solar powered systems, by the testing of various components in a real world environment, by the evaluation of various modifications to the components, and by the development of an optimum system design. Thus the program was to operate some 50 systems in as near to a real world environment as possible, in order to critically observe, measure and document all performance parameters. During 1973, details of the program were finalized, test instrumentation was procured, facilities were designed and constructed and late in the year, the systems to be evaluated were received. In the spring of 1974, all systems were placed in operation. In the following two years a considerable amount of data has been collected and the presentation of that data together with some conclusions and recommendations on solar energy, are the contents of this report.

2.0 PHYSICAL INSTALLATION

2.1 The Facility

A search was undertaken to find a suitable exposed platform with laboratory areas close by, which could accommodate the entire project. The University of Connecticut branch at Avery Point, Groton, Connecticut, where the R&D Center is located, was formerly a Coast Guard training base and there are several abandoned barracks on the campus. One of these appeared satisfactory and permission was granted by the University to use it. The building is two-story and the systems are located on the roof at the north end as shown in Figure 2.1-1. While the view to the north is somewhat obstructed, as shown in the figure, it is clear to the horizon in the east, and down to 10-15° above the horizon in the south and west. In the figure, all of the solar arrays are on the left side and the associated weather-proof boxes holding the storage batteries, voltage regulators and other circuitry is on the right. All of the arrays are mounted horizontally, since in actual use they would be horizontal. The buoy cannot be oriented to benefit from a tilted array and even on fixed aids they may be mounted flat to present a lower profile to vandals. Output cabling from all boxes leads to rooms one floor down where the loads and data-taking equipment are located. The insolation detectors are located in the northwest corner of the roof, just out of the picture to the left. The building is located about 200m from the waters of Fisher's Island Sound, at latitude 41°19'N, longitude 72°04'W.

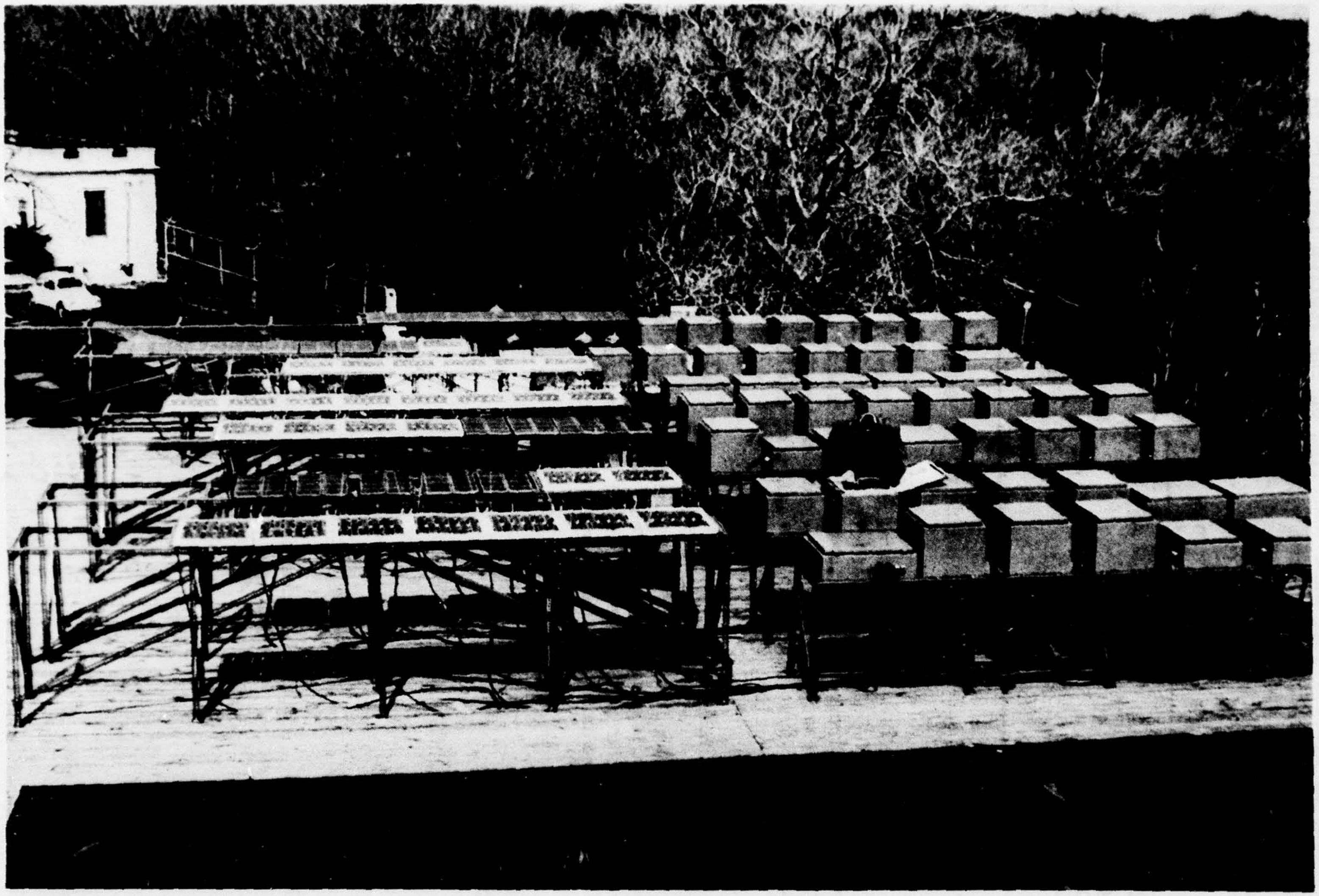


Figure 2.1-1. Rooftop Facility at Avery Point, North View

2.2 The Systems

The 53 systems that were installed on the rooftop facility in early 1974 were generally configured as shown in Figure 2.2-1.

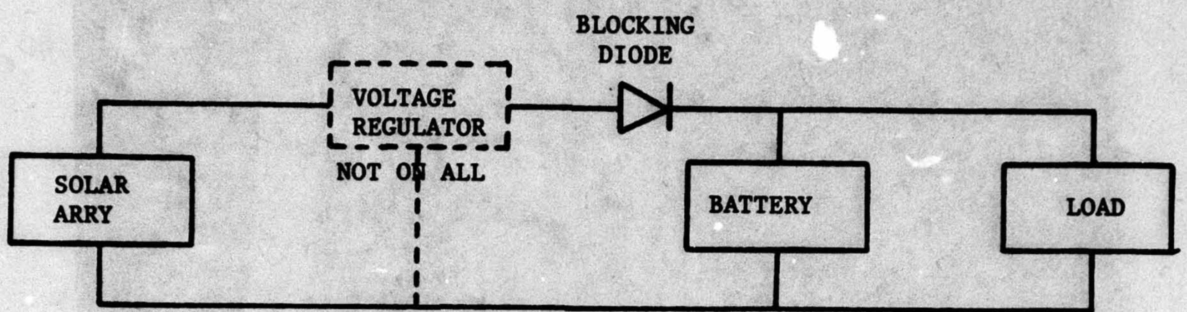


FIGURE 2.2-1 - GENERAL CONFIGURATION OF SYSTEMS

The specific description of each of the systems is found in Table 2.2-1. Coast Guard Headquarters procured all of each system except the load. We added the loads which were selected using certain estimates that were made in the first design approximation. For a full discussion see the section on system design. Details of the components are presented in the following section.

2.2.1 Solar Arrays

The individual solar cells are the silicon type. The packaging, however, was quite different between the two companies. In the Spectrolab array the cells are contained in plastic tubes. In the Centralab array the cells are under a glass cover and backed by a heavy metal plate.

	Spectrolab	Centralab
Photograph	Figure 2.2-2	Figure 2.2-3
Size	54.6 x 45.7 x 3.2cm	69.8 x 37.5 x 2.5cm
Weight	3.4kg	10.7kg
Cover	Lexan plastic tube	Glass
Internal Seal	Silicone Adhesive (RTV)	Silicone Adhesive (RTV)
Nominal Output	8 watts at 12 volts	8 watts at 12 volts

TABLE 2.2-1
SYSTEM DESCRIPTION

SYSTEM NUMBER	BATTERY TYPE/CAPACITY	ARRAY	LOAD	SYSTEM NUMBER	BATTERY TYPE/CAPACITY	ARRAY	LOAD
1	Globe/60	S	.55	28	Wisco/100	S	.77
2	Globe/60	S	.55	29	Wisco/100	S	.77
3	Globe/60	S	.77	30	Wisco/100	S	1.15
4	Wisco/100	S	.55	31	Gates/60	S	.55
5	Wisco/100	S	.77	32	Gates/60	S	.55
6	Wisco/100	S	1.15	33	Gates/60	S	.55
7	Gates/60	S	.77	34	Gates/60	S	.55
8	Gates/60	S	.55	35	Gates/60	S	.77
9	Gates/60	S	.55	36	Gates/60	S	.77
10	Gates/30	C	.25	37	Gates/60	S	.77
11	Gates/30	C	.55	38	Gates/30	C	.25
12	Gates/30	C	.55	39	Gates/30	C	.55
13	Globe/40	C	.25	40	Gates/30	C	.55
14	Globe/40	C	.55	41	Gates/30	C	.55
15	Globe/40	C	.55	42	Gates/30	C	.77
16	Wisco/26	C	.25	43	Gates/30	C	.77
17	Wisco/26	C	.55	44	Globe/40	C	.55
18	Wisco/26	C	.55	45	Globe/40	C	.55
19	Gates/60	S	.55	46	Globe/40	C	.55
20	Gates/60	S	.55	47	Globe/40	C	.55
21	Globe/60	S	.77	48	Globe/40	C	.77
22	Wisco/100	S	.55	49	Wisco/26	C	.25
23	Wisco/100	S	.55	50	Wisco/26	C	.55
24	Wisco/100	S	.77	51	Wisco/26	C	.55
25	Wisco/100	S	.77	52	Globe/40	C	.77
26	Wisco/100	S	.77	53	Globe/40	C	.77
27	Wisco/100	S	.77				

ARRAYS: S = SPECTROLAB; C = CENTRALAB

REGULATORS: Systems 1 through 18 are regulated.
Systems 1-9, Shunt Regulators; 10-18, Series Regulators

Battery capacity is in ampere-hours.

Load size is the continuous current rating of the lamp, in amperes.

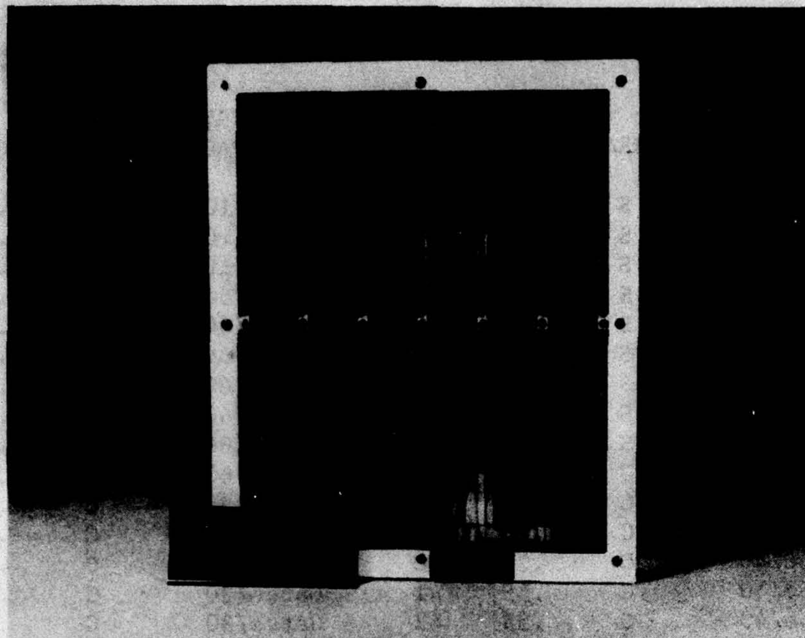


Figure 2.2-2. Typical Spectrolab Array

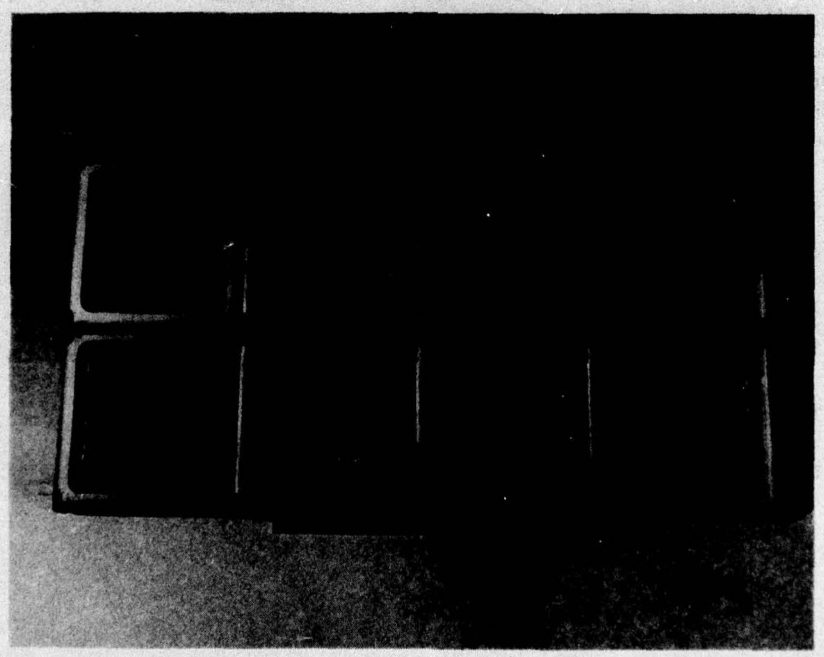


Figure 2.2-3. Typical Centralab Array

2.2.2 Batteries

The batteries are all of the lead-acid type but the Gates and Globe are sealed. The largest batteries used are described below.

	Globe	Gates	Wisco
Type	GC 12200	Special order	DD-3-3
Capacity in Amp-Hr	60	60	100
Current at rated capacity	1.0	0.5	0.25
Construction	3-12V, 20Ah Batteries in parallel for 12V, 60Ah	6-2V, 5Ah cells in series for 12V, 5Ah and 12 strings in parallel for 12V, 60Ah	2-6V, 100Ah Batteries in series for 12V, 100Ah
Size	17.5 x 49.8 x 12.5cm	48.8 x 30.7 x 9.5cm	46 x 18 x 24.5cm
Weight	22.8kg	29.6kg	36.4kg
Electrolyte	Jellied	Liquid contained in porous separator material	Liquid
Approximate Price Ratio	1.6	3.6	1.0

Figure 2.2-4 shows one Globe 12-volt, 20 amp-hour battery, the Gates 12-volt, 60 amp-hour battery, and two 6V, 100 amp-hour Wisco batteries with three Hydrocaps (Hydrocaps discussed in Section 3.3). In some power units smaller capacity combinations of the batteries were used. The price one must pay to get a sealed system is large; however, it may prove well worth it if there is a reduction in maintenance that is required.

Figure 2.2-4. Gates 12V, 60Ah battery, two Wisco 6V, 100Ah batteries and *Globe* 12V, 20Ah battery.

2.2.3 <u>Circuitry</u>

All systems have a blocking diode to prevent the battery from discharging through the array at night. In addition, about one-third were provided with a voltage regulator.

2.2.4 <u>Load</u>

The load presented to the battery was the same as would be in an actual aid to navigation - a tungsten lamp being flashed during the night by a solid-state timing and regulating circuit. The design section of this report covers the selection of the size (amperage) of the lamp.

2.3 Fixed Instrumentation

In the beginning it was not known which parameters would be most significant in affecting system operation so an attempt was made to measure as many as possible. Individual items to be measured daily were energy into and out of major components, operating voltage/current, temperature and solar insolation. A record of weather conditions for each day of operation was kept. Battery capacity, battery specific gravity and water use (where applicable) were taken manually, in standard ways and are discussed later.

2.3.1 Automatic Data Recording System

The term "automatic data recording system" is a descriptive title for a combination of electronic hardware and computer software specifically designed, constructed, and written for this laboratory evaluation of solar energy systems. The purpose of this automatic data recording system is to provide daily status reports on the 53 Spectrolab and Centralab solar energy systems being tested. The status reports contain voltage and ampere-hour battery capacities that are measured or calculated each day.

The electronic hardware portion of the automatic data recording system uses an electrical current integrating device that records the ampere-hours produced by a solar panel, ampere-hours delivered to a battery or ampere-hours consumed by a lamp flasher assembly. A total of 124 of these devices are used to monitor current flows throughout the 53 solar energy systems. The failure of these devices to reliably perform their function has caused data to be lost. A digital voltmeter is programmed to record the battery voltage of each system twice daily -- once during the early afternoon when on charge, and once during the latter portion of the nightly "lamp flash cycle." The second voltage measurement is taken during an actual lamp flash to insure a true loaded battery voltage measurement. The automatic recording of all data is coordinated by an electronic "Controller" designed and built by the R&D Center Electronics Branch. All data is recorded on punched paper tape.

The software portion of the automatic data recording system consists of a series of programs written in the Fortran V language of a Univac 1108 computer. The raw data recorded on the punched paper tape is entered into the program from a teletype terminal located at the R&D Center to a Univac computer at the Naval Underwater Systems Center in New London, Connecticut. The program produces a status sheet covering the condition of the 53 systems, as well as a series of diagnostic messages that warn of possible data recording malfunctions or possible solar energy system failures. Table 2.3-1 is an actual daily report. More details about the automatic data recording system are contained in Appendix A.

2.3.2 Insolation

In order to evaluate a solar system design it is necessary to be able to measure the amount of energy available to the solar array. The term used to describe this available energy is insolation and it is measured in Langleys in the English system or Joules/cm^2 in SI units: 1 Langley = 4.184 Joules/cm^2. Insolation is the time integral of solar

TABLE 2.3-1
DAILY SOLAR SUMMARY

SYSTEM NUMBER	SOLAR PANEL OUTPUT (AMP-HR)	REGULATOR OUTPUT (AMP-HR)	LOAD INPUT (AMP-HR)	V(DAY) (VOLTS)	V(LOAD) (VOLTS)	ESTIMATED BATTERY CAPACITY (AMP-HR)
1	.92	.81	.93	12.57	12.08	45.29
2	.61	.44	.83	12.65	12.17	34.72
3	1.01	.94	1.27	12.88	12.26	34.07
4	.77	.04	.90	12.08	11.81	26.48
5	.82	.76	1.53	12.65	12.07	36.55
6	.88	.24	.07	9.84	****	91.32
7	1.12	1.06	1.38	12.83	12.23	36.43
8	.66	.52	1.08	12.52	12.12	33.47
9	.78	.70	.97	13.02	12.48	43.26
10	.70	.46	.02	13.31	12.77	30.01
11	.70	.61	.99	13.03	12.46	20.78
12	.69	.59	.99	13.07	12.45	22.40
13	.70	.00	.35	13.33	12.59	37.69
14	1.04	.99	.86	13.11	12.51	29.36
15	1.18	1.10	1.13	13.13	12.52	21.74
16	.72	.53	.47	13.38	12.49	16.84
17	1.17	1.08	.92	13.06	12.19	18.69
18	1.18	1.17	1.00	13.00	12.10	14.24
19	1.07	-	1.17	13.21	12.52	43.52
20	1.06	-	1.11	13.20	12.60	46.83
21	.85	-	1.34	12.82	12.20	34.73
22	.84	-	.95	13.26	12.51	79.51
23	.86	-	.95	13.16	12.51	81.45
24	1.06	-	1.45	12.96	12.32	69.88
25	1.00	-	1.04	13.04	12.44	81.45
26	1.20	-	1.31	13.03	12.35	75.34
27	.59	-	1.43	12.90	12.27	68.20
28	.63	-	1.44	12.86	12.29	61.47
29	1.04	-	1.33	13.11	12.40	71.81
30	.93	-	1.17	12.50	11.94	34.47
31	1.06	-	.96	13.23	12.57	48.17
32	.82	-	.95	13.23	12.61	53.56
33	1.00	-	.95	13.24	12.59	46.65
34	1.11	-	.82	13.24	12.58	49.17
35	.89	-	1.34	12.58	12.08	30.69
36	.87	-	.97	12.83	12.27	43.83
37	.75	-	.71	12.53	12.00	31.21
38	.94	-	.47	14.30	12.82	27.51
39	1.22	-	.81	13.23	12.60	24.55
40	1.12	-	.92	13.21	12.58	22.55
41	1.24	-	.80	13.20	12.57	24.37
42	1.06	-	1.38	12.42	11.85	3.10
43	.63	-	1.31	12.81	12.17	3.43
44	1.18	-	.99	13.20	12.52	31.95
45	1.24	-	.99	13.25	12.58	31.69
46	1.17	-	.86	13.26	12.59	33.15
47	1.27	-	.97	13.03	12.44	32.07
48	1.06	-	.05	12.15	****	27.62
49	1.25	-	.47	14.27	12.67	24.16
50	.64	-	.98	13.23	12.29	9.95
51	.82	-	.96	13.26	12.32	13.37
52	1.35	-	1.17	13.07	12.34	25.49
53	1.33	-	1.35	12.99	12.31	23.69

SPECTROLAB STANDARD CELL: 107.60 LANGLEYS
CENTRALAB STANDARD CELL: 205.12 LANGLEYS

irradiance. Insolation data for various geographic locations are available from many government and private sources on a per hour, day or month basis. Since there is no long-term insolation data available for the Groton area, it was necessary to base initial calculations of system performance on data from Newport, Rhode Island, which is considered to be similar to the Groton area. Short-term data for monitoring day-to-day system operation and for comparison with Newport was to be obtained by suitable instrumentation installed on the roof of the test facility. To this end, two Eppley model PSP pyranometers were purchased and installed. They are temperature compensated to render the response essentially independent of ambient temperature. The output which is in the 10 mV D.C. range, is time integrated by a Monitor Labs Model #5130 Integrating Printer, which provides insolation at 60-minute intervals, identified by day and hour. To back up the pyranometer, one calibrated silicon standard cell from each of the two manufacturers was mounted beside the pyranometers. The output of the standard cells are integrated by Curtis Automatic Coulometers which are discussed in Appendix A. The pyranometers and the standard cells are cleaned daily. There were early problems with the Integrating Printer but they were corrected and, except for five or six days when power failures occurred, our insolation records are continuous from mid-August 1974.

The pyranometers were calibrated by The Eppley Laboratory, Inc., #12570 in July 1973 and #13036 in April 1974. The daily insolation is taken as the average of their outputs which have been consistently in close agreement; less than 3 percent difference. We have been able to obtain insolation data from Eppley for Newport and the comparison is interesting. Everyone has seen the sun shine on one side of the street and not on the other, and there were predictions that areas displaced by only a few miles would have vastly different insolation levels. Figure 2.3-1 shows how the insolation compared between Groton and Newport for the period from mid-June 1975 through December 1975, and how some days may be quite different. However, the symmetrical distribution around zero indicates very little long-term difference. Table 2.3-2 gives the monthly totals for the same time period.

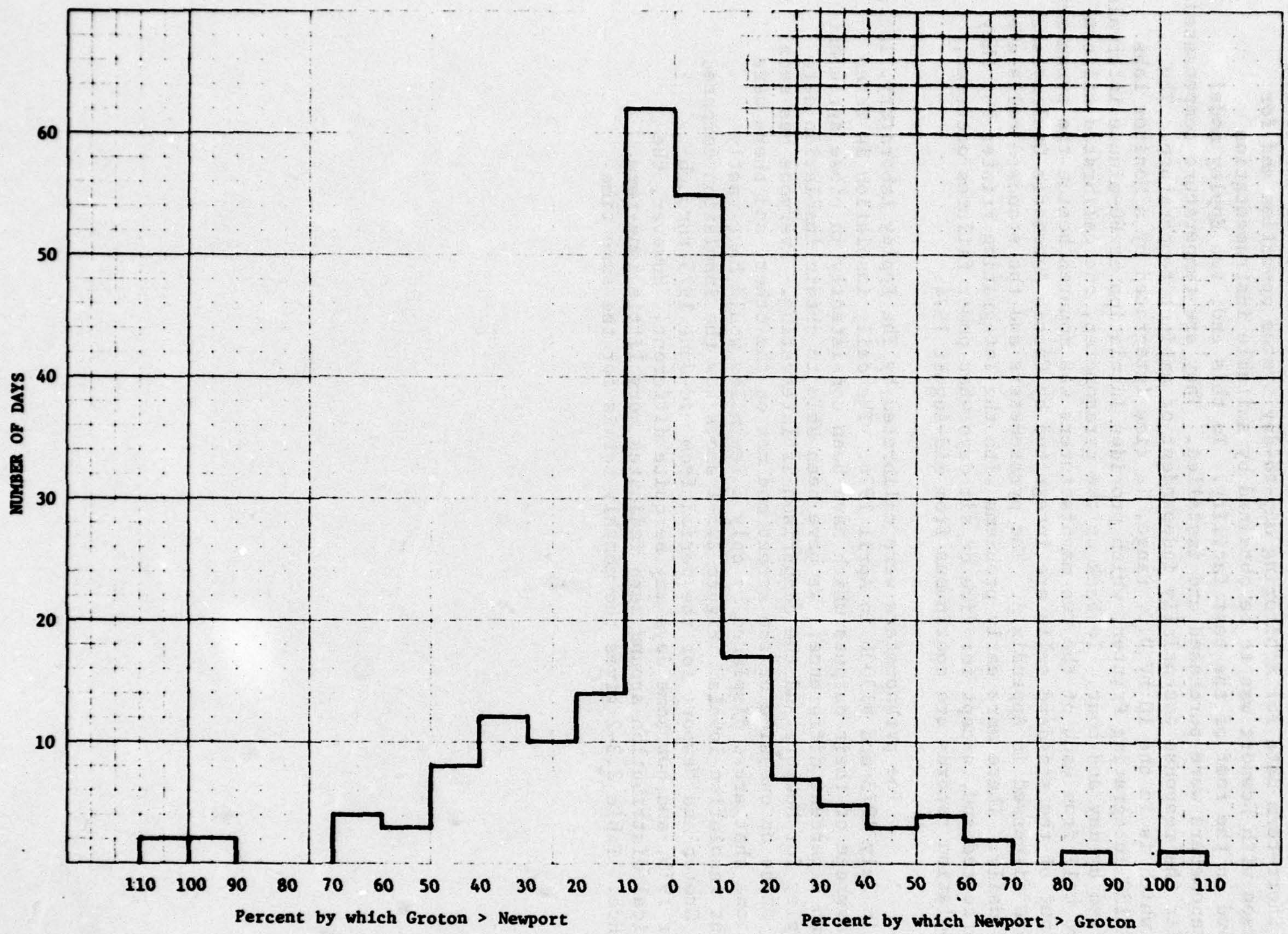


FIGURE 2.3-1 - COMPARISON OF INSOLATION
GROTON - NEWPORT, JULY - DECEMBER 1975

Table 2.3-2 Insolation in J/cm^2

	Groton	Newport	G/N
15-30 Jun	33310	35140	.95
Jul	66120	63110	1.05
Aug	52320	50860	1.03
Sep	39960	36940	1.08
Oct	30530	30380	1.00
Nov	21220	21160	1.00
Dec	15370	14860	1.03
Total	258830	252450	1.025

Because of its different spectral sensitivity, the standard cell will not give the same response to sunlight as the pyranometers. But, through a long period of side-by-side operation, we have derived empirically a factor that adjusts the standard cell output to give the insolation. The adjusted cell output agrees with the pyranometer to ± 2 percent and allowed the Integrating Printer to be sent out for repairs in February, 1975, without a loss of data.

The Spectrolab standard cell was not hermetically sealed and condensation was observed between the cell and the cover glass soon after it was installed. Twice, standard cells were returned to Spectrolab for repair and when this did not work, they were dropped from the test. Except for some corrosion on the housing, the Centralab standard cells have had no problems.

2.3.3 Temperature

It is recognized that almost all of the measurements and observations that we would make were affected by changes in temperature. In order to discover any large or unexpected variations, a multi-channel chart recorder was set up to record the temperature registered by copper-constantan thermocouples at several locations. Ambient as well as temperatures in three battery boxes and one liquid electrolyte battery were measured. The temperatures are still being taken, but to date there have been no unexpected variations in other system parameters that can be attributed to changes in temperature. Temperature corrections are routinely made to electrolyte specific gravities and to solar array outputs that are measured periodically for comparison purposes (see Section 3.1).

The battery boxes as received from Centralab and Spectrolab were all painted a machinery gray color. This gray color is similar to that of the plastic boxes which hold batteries on shore aids. In order to determine if a temperature reduction could be affected, some of the battery boxes, including one with a thermocouple, were repainted white. Data, taken during the first summer of operation, indicate that the maximum temperature in the white battery boxes was reduced by about 10°C. Although we have not been able to measure any short-term effects, such as changes in capacity or water usage, the higher temperatures of the gray boxes should cause greater local action in the batteries. This may not be too important in our system but in the primary batteries currently in use on aids, the loss in capacity could be significant.

Since we had not been able to detect any changes caused by the difference in temperature, it was decided to paint all of the boxes white and eliminate that one small variable in the test.

2.3.4 Manual Coulometers

At each point of interest in the system, where data on the time integrated current was desired, there was placed an "automatic" coulometer and to back up each one of these was a "manual" coulometer. The principle of operation is the same for both types and is described in Appendix A. The difference is in the readout. In the manual coulometers, the glass tube with the mercury is mounted on a fixed scale graduated in amp-hours and the difference in location of the electrolyte bubble from one reading to the next, determines the total number of amp-hours. Manual coulometers were chosen because they required no external source of power and could be read without special equipment. The manual coulometers were located in the battery boxes on the roof of the test facility. They registered a total of 1000 amp-hours in a total of less than two inches of travel of the electrolyte gap. We wanted to read them monthly which could be a change of 10 to 150 amp-hours depending on the current being measured - load, array or battery. To get the required resolution it was necessary to photograph the manual coulometer and to read the photographs with a binocular microscope. It was then determined this far exceeded the inherent accuracy of the coulometers. It became apparent the accuracy was affected by many sources of error such as temperature, variation of tube diameter and gap width, pulsed current effects, mercury contamination, non-linearity with current levels, etc. While it might be possible to calibrate the individual coulometers to negate some of the error sources the calibration would be a large task. Another problem that developed with the manual coulometers was failure, either of the current shunt or the tube itself. This in turn created an open circuit and caused failure of the solar system itself. Because of these failures and the manual coulometer inaccuracy it was decided to abandon their use and they were removed from all systems.

3.0 PROCEDURES AND DATA

The following sections describe how we monitored the operation of the systems and components and presents some of the data collected.

3.1 Solar Arrays

The arrays supplied by each manufacturer are very different. Each Spectrolab array is made up of six independent modules, and each module is made up of 1cm x 2cm silicon cells connected five in parallel to form rows, which in turn are connected in series with other rows to increase the module voltage. The cells in the module are encapsulated in a UV-resistant Lexan plastic tube. The connections between the individual silicon cells are made with an "expanded metal" copper mesh that is soldered from the bottom of one cell to the top of the next. The modules are then connected three modules in parallel, in series with the other three modules in parallel (Figure 3.1-1).

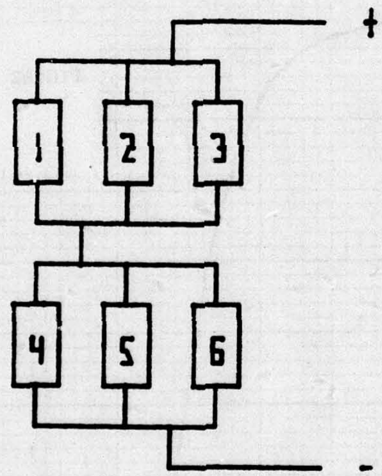


Figure 3.1-1. Spectrolab Module Configuration

The output as measured by Spectrolab for a typical new array is shown in Figure 3.1-2. A photograph of the array is shown as Figure 2.2-2.

The Centralab arrays are comprised of eight modules, rated at 1-watt each by the manufacturer. Each module consists of 36 2cm x 2cm silicon cells, connected 12 in series and then three of these in parallel. Some of the series connections are made by a "shingle" arrangement. The cells are then placed face down in the bottom of a borosilicate glass "dish" and completely sealed from the back by filling with RTV. Teflon-covered wires lead through the RTV from the cells and the modules are connected as two parallel strings of four modules in series (Figure 3.1-3). The modules are mounted on a heavy aluminum plate.

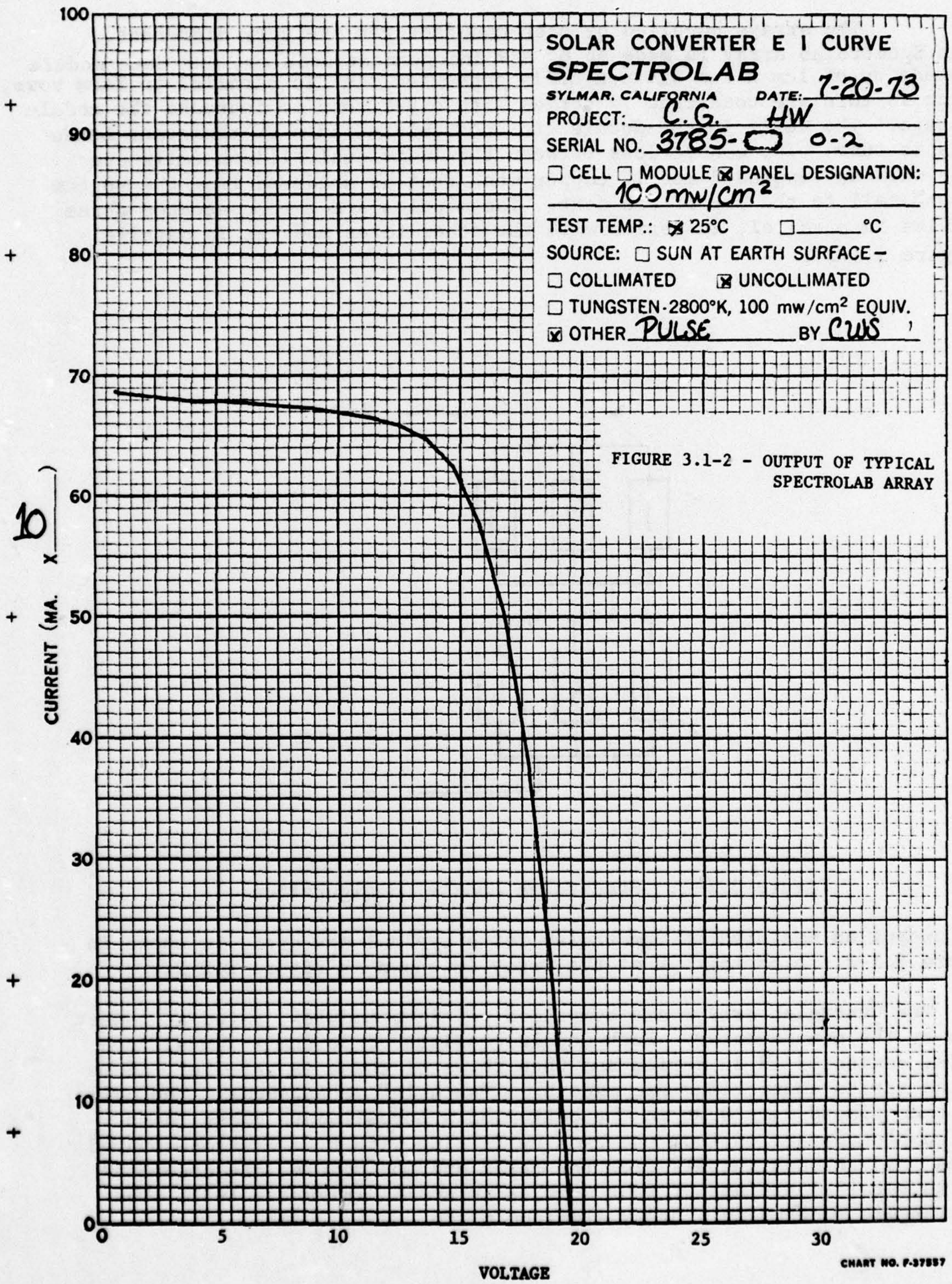


FIGURE 3.1-2 - OUTPUT OF TYPICAL SPECTROLAB ARRAY

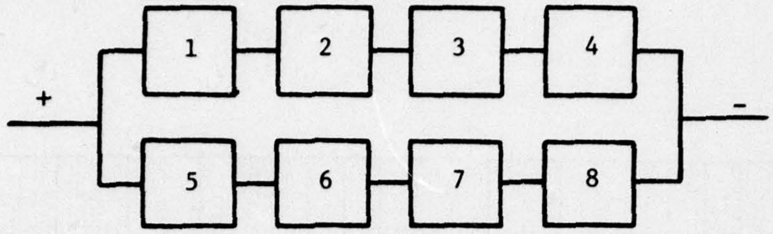


Figure 3.1-3. Centralab Module Configuration

There is a rubber gasket between the module glass plate and the aluminum base plate. Each module is sealed with RTV to the base and held down tightly by a metal ring that is pulled down with screws from the underside of the base plate. Under one module the wires are brought together and soldered to two terminals which lead through the array base plate to an external connection block. A photograph of the array is shown as Figure 2.2-3. The output as measured by Centralab for a typical new array is shown in Figure 3.1-4.

In order to follow the performance of each array, it is necessary to measure the output periodically. For these measurements, the array output is connected to a variable resistance and the current and voltage are measured from no load to full load (Figure 3.1-5). The array is not tilted but remains horizontal for this measurement; zero cloud cover is required before beginning data collection.

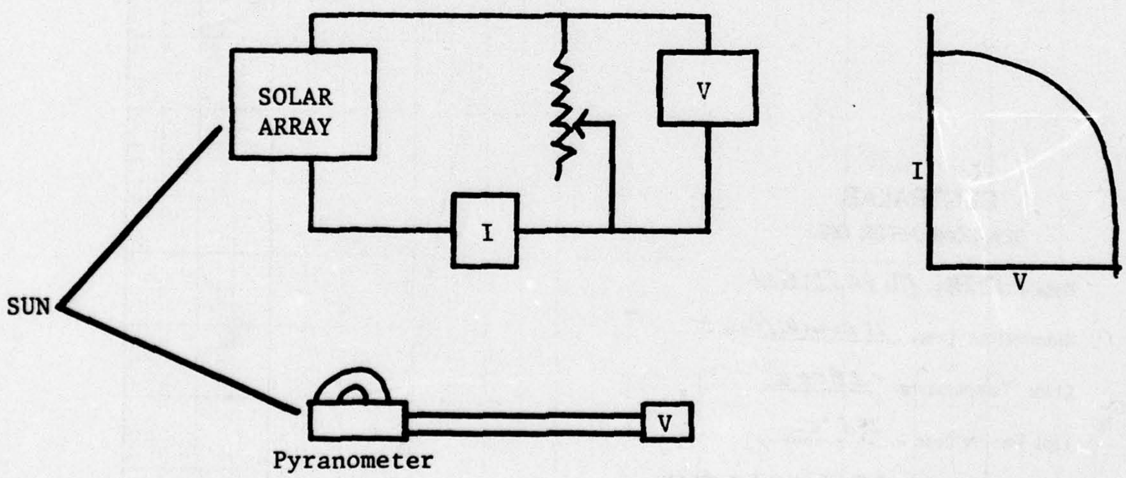


FIGURE 3.1-5 - INSTRUMENTATION FOR I-V CURVE MEASUREMENT

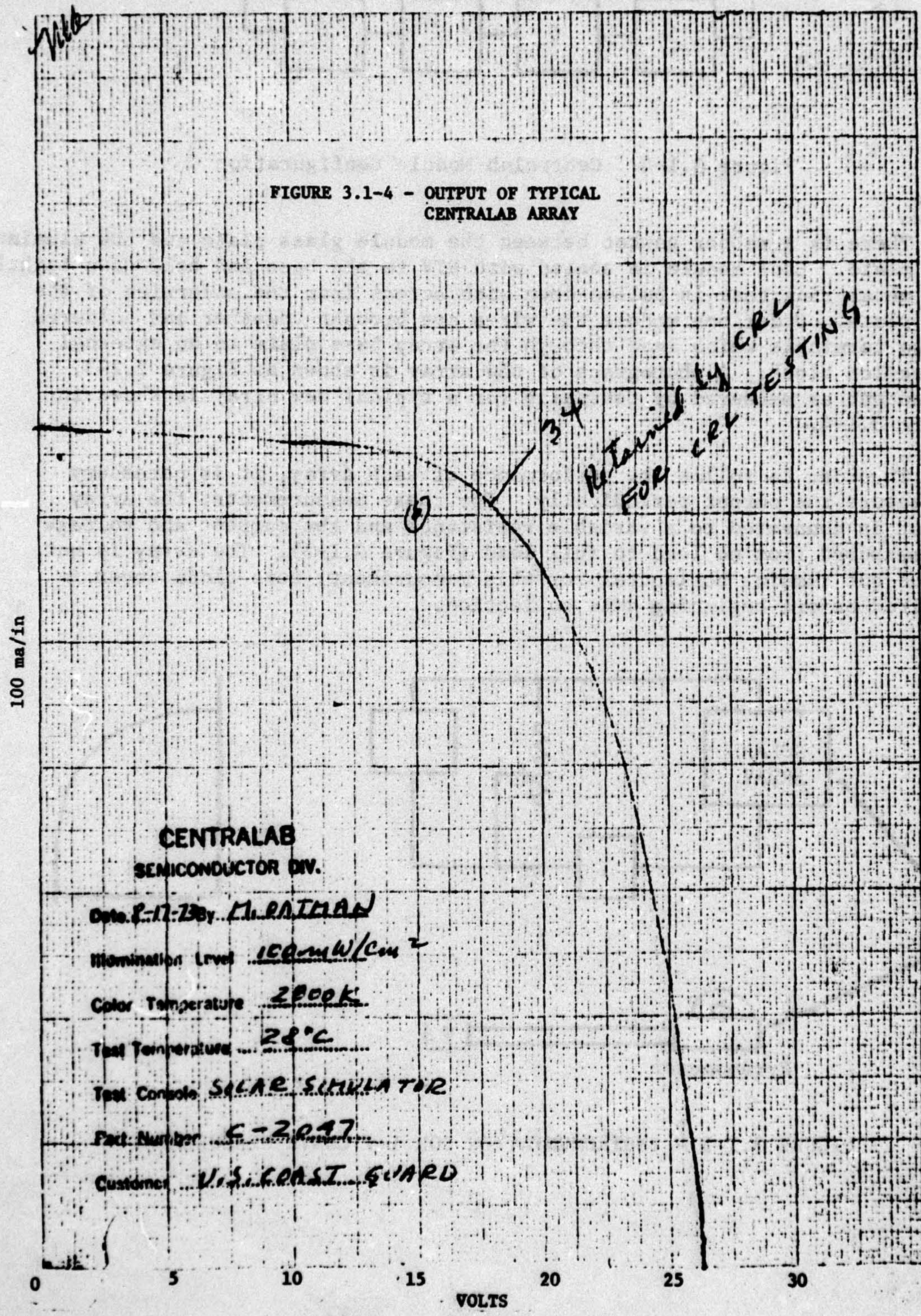


FIGURE 3.1-4 - OUTPUT OF TYPICAL CENTRALAB ARRAY

Two corrections are made to the I-V curve that is generated. The first correction is for irradiance level, with the Eppley pyranometer as the standard. The output of the pyranometer is measured with a millivoltmeter at the same time as the array I-V curve is measured. The irradiance level measured by the pyranometer is then used to increase the array output to what it would be when irradiated with 100 mW/cm^2. This correction is only applied to current output which varies linearly with irradiance. Because the voltage correction is non-linear and small, it is not made to the output.

An additional correction must be made to voltage and current to compensate for the fact that the array temperature may vary from standard conditions. The array output is corrected to 25°C by using a positive temperature coefficient of current of 0.15 percent/°C, and a negative temperature coefficient of voltage of 0.4 percent/°C. We cannot measure the cell temperature directly, but assume it is higher than ambient by a ΔT that is proportioned to the irradiance level. A maximum of 14°C at 100 mW/cm^2 incident is used.

$$T = T_A + 14(I/100)$$

T = array temperature in °C

T_A = ambient temperature in °C

I = irradiance in mW/cm^2

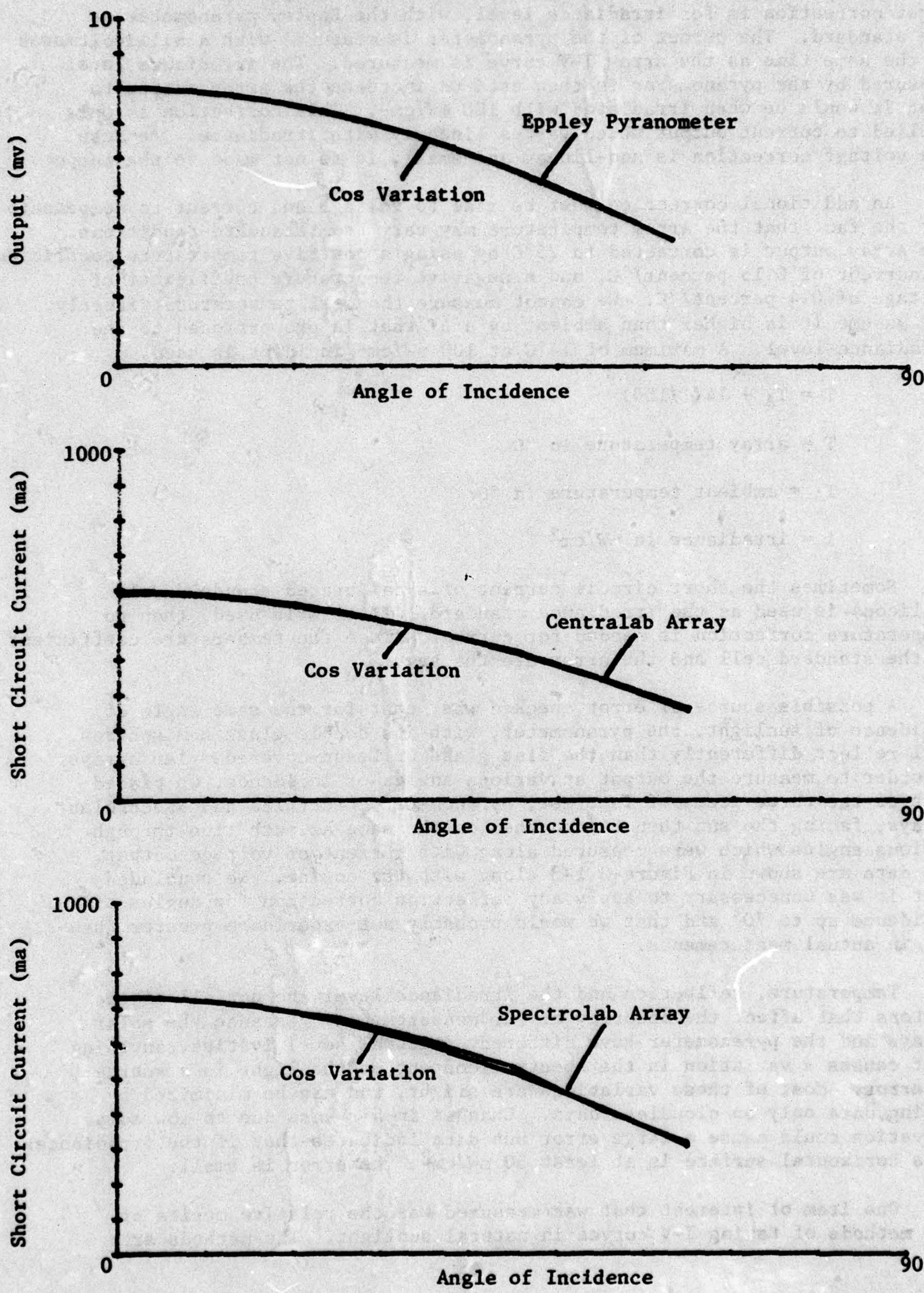
Sometimes the short circuit current of a calibrated standard cell (silicon) is used as the irradiance standard. If this is used, then no temperature correction is needed for current, since the temperature coefficient of the standard cell and the array are the same.

A possible source of error checked was, that for the same angle of incidence of sunlight, the pyranometer, with its double glass hemispheres, will reflect differently than the flat glass or Lexan-covered solar arrays. In order to measure the output at various angles of incidence, we placed each of the three items of interest, pyranometer, Centralab and Spectrolab arrays, facing the sun then tilted them on the same azimuth line through various angles which were measured along with current or voltage output. The data are shown in Figure 3.1-6 along with the cosine. We concluded that it was unnecessary to apply any reflection correction for angles of incidence up to 70° and that we would probably not experience greater than 65° in actual measurements.

Temperature, reflection and the irradiance level are not all of the factors that affect the accuracy of our measurements. Because the solar arrays and the pyranometer have different spectral sensitivities, anything that causes a variation in the spectral content of the light is a source of error. Most of these variations are slight, and can be minimized by taking data only on cloudless days. Changes in air mass due to low solar elevation could cause a large error but data indicates that if the irradiance on a horizontal surface is at least 50 mW/cm^2, the error is small.

One item of interest that was measured was the relative merits of two methods of taking I-V curves in natural sunlight. The methods are:

FIGURE 3.1-6 - OUTPUT VARIATION WITH ANGLE OF INCIDENCE IN SUNLIGHT



(1) using a horizontal Epply pyranometer to normalize the output of a horizontal array, to equivalent output at 100 mW/cm^2, and (2) peaking the array towards the sun and using a silicon standard cell, mounted in the same plane, to normalize its output to 100 mW/cm^2. The results of that comparison are shown in Figure 3.1-7. The comparison was conducted on 29 September 1975 with a Spectrolab array comprised of Lexan-covered modules. All I-V curves are normalized to 100 mW/cm^2 at 25°C.

Curve (1) was taken at 1315 with the array level, on a clear day in the fall, the Eppley as the standard, and 68 mW/cm^2 incident on a horizontal surface. The array was then peaked into the sun and Curve (2) was measured with the standard cell indicating 96 mW/cm^2 incident on the array. Curve (3) was made two hours later, at 1515, with the array level and the Eppley indicating 51 mW/cm^2 incident. We concluded that for the accuracy we needed (±10%), if we set minimum requirements of clear skies and 50 mW/cm^2 incident on a horizontal surface, the two methods were identical.

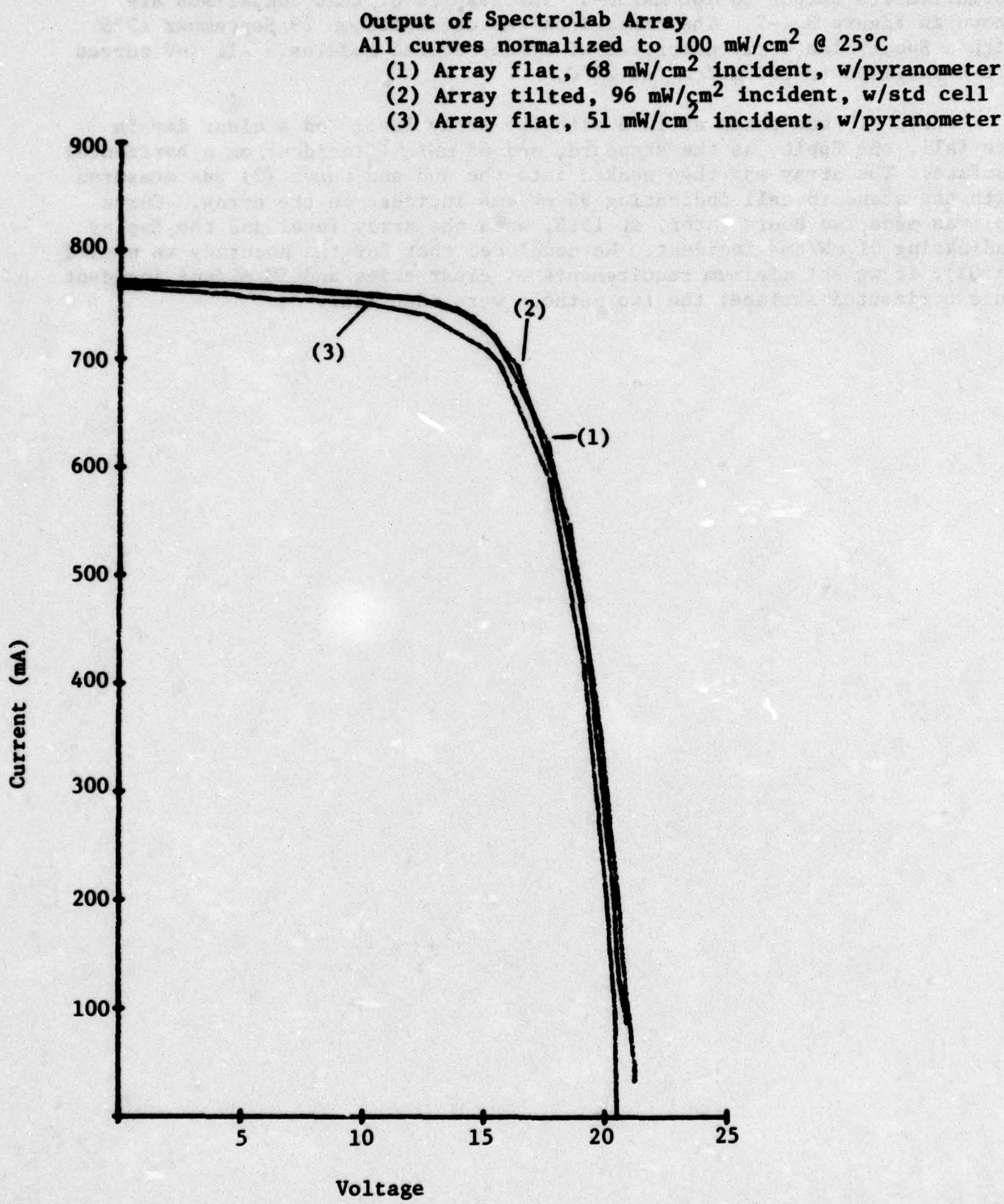


FIGURE 3.1-7 - COMPARISON OF TWO METHODS OF TAKING I-V CURVES IN NATURAL SUNLIGHT

Table 3.1-1
ARRAY OUTPUT; percent of NEW

ARRAY #	SPECTROLAB @ 0.0 V 12 SEP 74	11 NOV 74	6 DEC 74	14 JAN 75	21 MAR 75	27 MAR 75	SPECTROLAB @ 13.5 V 12 SEP 74	11 NOV 74	6 DEC 74	14 JAN 75	21 MAR 75	27 MAR 75
1	78	60	66	87	66	72	78	60	62	90	61	60
2	42	47	72	72	63	67	30	32	46	52	39	40
3	78	70	92	94	83	84	76	72	80	89	76	76
4	34	53	46	58	54	51	33	50	39	55	--	42
5	45	48	76	92	52	35	45	46	71	86	51	36
6	83	87	83	87	80	--	82	85	76	86	82	--
7	93	94	92	92	90	--	91	87	87	89	85	--
8	33	35	53	60	33	55	30	30	37	49	29	38
9	75	66	60	73	67	67	73	61	54	67	61	62
19	98	101	84	90	96	--	98	103	81	95	96	--
20	98	104	100	96	100	--	90	103	96	97	100	--
21	85	89	91	97	81	--	78	86	86	95	81	--
22	96	99	95	93	97	--	91	97	93	92	90	--
23	54	65	85	82	58	67	43	59	82	78	--	55
24	83	82	85	83	78	--	83	84	85	90	83	--
25	80	96	87	90	94	--	80	95	87	92	94	--
26	103	104	95	97	101	--	99	102	94	98	99	--
27	79	88	89	92	72	80	65	68	80	82	68	80
28	--	97	96	91	93	--	--	92	92	90	91	--
29	102	102	96	94	100	--	97	101	94	93	98	--
30	63	70	81	85	59	69	63	67	76	88	--	71
31	98	100	81	92	97	--	84	98	83	92	97	--
32	99	102	92	91	95	--	92	99	83	89	91	--
33	86	92	93	93	94	--	82	92	86	87	91	--
34	104	105	96	97	102	--	101	103	92	97	101	--
35	67	78	90	83	78	--	54	81	80	76	58	--
36	88	89	83	83	88	--	85	86	81	85	82	--
37	42	52	74	83	49	65	43	53	67	78	50	56
TEMP °C	18	15	6	0	9	-2						
MAX INSOL mW/cm^2	83	45	41	50	80	82						
MIN INSOL mW/cm^2	75	42	21	49	72	79						

Table 3.1-1 (Cont'd)

ARRAY #	SPECTROLAB @ 0.0 V 28 MAY 75	1 JUL 75	19 AUG 75	29 SEP 75	28 OCT 75	12 FEB 76	SPECTROLAB @ 13.5 V 28 MAY 75	1 JUL 75	19 AUG 75	29 SEP 75	28 OCT 75	12 FEB 76
1	57	57	--	43	57	54	57	47	--	43	53	50
2	41	35	--	34	31	--	29	23	--	23	23	--
3	65	67	--	61	68	83	57	58	--	59	59	78
4	33	34	--	--	--	--	33	33	--	--	--	--
5	33	34	--	--	--	--	34	35	--	--	--	--
6	80	75	--	--	--	--	81	75	--	--	--	--
7	78	75	--	54	60	70	70	73	--	49	49	56
8	--	--	--	--	--	--	--	--	--	--	--	--
9	66	68	--	62	64	50	63	65	--	58	61	47
19	81	94	--	86	98	96	82	95	--	85	88	97
20	75	74	--	54	85	88	76	70	--	48	86	76
21	74	66	--	66	69	89	69	65	--	65	61	86
22	76	82	--	84	86	97	74	79	--	79	82	95
23	40	41	--	--	--	--	36	36	--	--	--	--
24	73	77	--	--	--	--	78	81	--	--	--	--
25	72	82	--	--	--	--	71	79	--	--	--	--
26	99	102	101	100	97	99	93	98	91	95	96	96
27	47	56	--	18	--	--	37	48	--	15	--	--
28	91	86	--	88	88	76	84	80	--	83	81	72
29	95	97	98	99	98	100	92	97	96	96	96	99
30	49	49	--	40	33	48	47	47	--	40	29	44
31	89	90	--	79	92	94	81	86	--	73	74	80
32	84	84	--	67	80	89	85	85	--	65	79	84
33	70	68	--	49	81	91	69	63	--	55	98	83
34	100	100	102	103	103	98	96	93	98	99	18	98
35	37	35	--	12	27	58	22	31	--	8	73	48
36	78	81	--	69	74	--	72	79	--	73	44	--
37	33	33	--	37	35	34	34	34	--	36		34
TEMP °C	26	25	26	23	17	3						
MAX INSOL mW/cm2	94	95	87	71	55	58						
MIN INSOL mW/cm2	86	78	75	70	51	53						

Table 3.1-1 (Cont'd)

ARRAY #	CENTRALAB @ 0.0 V 12 SEP 74	11 NOV 74	6 DEC 74	14 JAN 75	21 MAR 75	27 MAR 75	CENTRALAB @ 13.5 V 12 SEP 74	11 NOV 74	6 DEC 74	14 JAN 75	21 MAR 75	27 MAR 75
10	93	95	87	91	91	--	89	94	86	88	90	--
11	96	98	91	89	94	--	94	98	90	89	94	--
12	96	97	91	94	95	--	94	96	89	92	93	--
13	98	98	90	93	97	--	96	98	90	93	96	--
14	95	97	89	91	94	--	93	96	88	90	--	--
15	97	102	88	94	96	--	97	103	88	94	96	--
16	96	101	86	93	94	--	94	101	86	92	94	--
17	95	101	86	93	94	--	93	101	86	93	92	--
18	97	102	88	92	95	--	95	103	88	92	95	--
38	100	105	97	93	95	--	97	105	96	92	96	--
39	100	104	97	96	94	--	97	104	96	94	94	--
40	93	100	92	93	93	--	95	100	91	93	91	--
41	99	101	93	94	94	--	97	102	92	94	94	--
42	82	86	78	78	79	--	82	86	78	79	79	--
43	98	102	91	92	98	--	97	101	91	91	--	--
44	97	99	90	93	93	--	95	99	87	92	--	--
45	98	102	96	96	100	--	94	99	93	95	--	--
46	98	100	95	94	92	--	94	99	93	94	--	--
47	--	101	95	93	96	--	--	102	94	94	96	--
48	96	102	91	94	95	--	93	101	90	94	--	--
49	97	101	96	95	94	--	93	101	94	94	--	--
50	95	101	92	93	90	--	93	100	91	93	--	--
51	84	88	86	97	94	--	83	88	85	98	93	--
52	--	103	100	96	95	--	--	104	98	94	95	--
53	98	103	99	98	94	--	96	103	98	98	93	--
TEMP °C	18	15	6	0	9							
MAX INSOL mW/cm^2	83	45	41	50	80							
MIN INSOL mW/cm^2	75	42	21	49	72							

Table 3.1-1 (Cont'd)

ARRAY #	CENTRALAB @ 0.0 V						CENTRALAB @ 13.5 V					
	28 MAY 75	1 JUL 75	19 AUG 75	29 SEP 75	28 OCT 75	12 FEB 76	28 MAY 75	1 JUL 75	19 AUG 75	29 SEP 75	28 OCT 75	12 FEB 76
10	87	90	94	92	89	93	87	87	92	90	86	88
11	88	90	94	95	91	93	87	88	93	93	91	90
12	90	90	96	96	93	95	86	86	92	92	89	89
13	91	91	98	98	94	101	88	90	95	93	91	89
14	91	91	97	95	93	96	90	90	96	93	90	89
15	89	90	98	98	95	98	89	90	97	96	95	99
16	88	90	98	98	95	99	88	89	96	95	93	97
17	--	--	98	101	98	101	89	--	89	87	92	96
18	90	93	99	97	94	98	89	92	97	94	93	98
38	92	93	97	99	99	98	92	93	96	97	99	97
39	92	94	97	98	98	97	91	92	95	95	97	96
40	92	94	95	95	96	94	90	91	90	92	94	92
41	93	95	97	98	103	102	91	94	95	96	102	102
42	79	80	82	81	90	83	78	78	81	78	88	82
43	94	96	98	98	104	102	93	94	96	95	104	101
44	95	--	100	99	99	95	83	--	94	94	95	94
45	95	97	99	99	101	98	90	90	92	92	95	96
46	94	95	97	99	100	97	91	91	93	93	98	96
47	92	94	96	99	97	95	91	93	94	94	97	94
48	96	97	98	100	100	98	94	96	96	96	98	96
49	96	97	100	99	99	100	86	88	89	90	94	98
50	93	94	96	95	96	93	90	91	93	92	93	92
51	94	97	102	103	105	97	93	95	101	100	104	96
52	94	95	97	97	100	97	94	94	96	96	99	96
53	95	96	98	99	101	98	91	92	94	95	99	97
TEMP °C	26	25	26	23	17	3						
MAX INSOL mW/cm^2	94	95	87	71	55	58						
MIN INSOL mW/cm^2	86	78	75	70	51	53						

After the data is taken on each of the arrays and normalized to 100 mW/cm^2 at 25°C, it is compared to the previous measurements and to the manufacturer's claim of output when new. Because it is inconvenient to compare many pages of curves, the current output at 0.0V and at 13.5V is recorded in tabular form. If there are changes that warrant a detailed examination, the entire curve can be drawn. A representative sample of the measured array output shown in Table 3.1-1, as a percentage of the current claimed by the manufacturer. Spectrolab provided a separate I-V curve for each array. Each percent output for Spectrolab is for its corresponding original curve. Centralab plotted ten I-V curves per page and it was not possible to distinguish each array's curve. Therefore, each percent output for Centralab is for an "average" original curve and all arrays are compared to the same standard. Also tabulated in Table 3.1-1 are temperature and max-min insolation levels during the measurements. Even though each array is corrected individually for irradiance level, the lower the difference between max-min, the better the relative comparison of the day's data. Also, since lower irradiance implies lower sun elevation and higher air mass, for which no correction is applied, the higher irradiance days should give a better absolute comparison of the day's data.

An examination of Table 3.1-1 will show that the Spectrolab arrays have major problems. Not only are their outputs low but they are also erratic. At various times we thought these problems were attributed to natural degradation of the packaging, defects in our measurement technique or to bubbles in the index-matching filler that is in the Lexan tubes. We now believe the problem to be in the intercell connections within the Lexan tube. These connections are all made by soldering strips of "expanded metal" copper mesh between the cells. The solder joints are very poor, the copper is not completely tinned, and the solder connections appear to be "cold" in many places. This bad soldering is compounded by the direction of orientation of the copper mesh. The copper mesh used has an elongated diamond-shaped lattice, resembling a chain-link fence.

Inspection of this or any other "expanded metal" shows that it is very stiff in the direction of the long axis of the diamond when compared to the flexibility in the direction of the short axis. Most of the modules in the Spectrolab arrays are made with all of the copper mesh inter-connections oriented in the same direction within each module. In some modules, the long axis is in the direction of the series connection and in others it is turned 90°. As a shorthand, we denote those modules with the long axis of the mesh in the direction of the series connection to be "stiff," while those with the short axis in that direction are called "flexible."

Because of Spectrolab's method of connecting the modules (see Figure 3.1-1), it is possible to measure each module separately by covering any two in a parallel group and then equating the total array output to that of the uncovered module. Table 3.1-2 shows the output of the modules of the 20 arrays which were on the roof in November 1975. Spectrolab provided two different types of arrays; the arrays used with a voltage regulator have all six modules with 20 cells in series, while the arrays for use without regulation have three modules with 12, 13 or 14 cells in series in an attempt to match the output voltage to the voltage of the particular battery manufacturer (see Figure 2.2-2). Both the "long" and the "short" modules are made with "flexible" or "stiff" interconnections. Three modules had "flexible" and "stiff" interconnections within them and are not included in the table.

Spectrolab did not provide data on individual modules but we estimate that nominal output would be 250-265 ma. The cell interconnect must change direction twice in a very short distance and it appears that if the copper mesh is oriented in the "stiff" direction the stresses created by the shock of handling and temperature cycling are transmitted from cell to cell by the mesh rather than being absorbed in it. These stresses break and remake the poor solder connections and cause the erratic, decreasing array output shown in Table 3.1-1. The "short" modules that were measured appear to be soldered a little better than the long ones, and some later generation arrays purchased from Spectrolab (before they began using round cells) show marked improvement in their soldering techniques. On the later generations, not only is every cell interconnection made with the copper mesh in the "flexible" direction, but the solder joints are complete across the width of the cell. The solder is bright and shiny, indicating a good electrical and mechanical connection. Those arrays of the later generations have shown none of the faults of earlier types.

Because of the erratic and low output of most of the Spectrolab arrays it has been impossible to gather any data that is useful in design or component evaluation. Accordingly, all but three of the original Spectrolab arrays have been dropped from the test. The three arrays retained showed consistent high output; and investigation revealed they were the only arrays to be comprised of six modules, all with flexible intercell connections. In Table 3.1-1 they are arrays #26, #29 and #34.

It is disappointing after a two-year exposure to have so many arrays fail. In fact, since the arrays were not measured before they were installed or during the first few months of exposure because no problems were suspected, we do not know when the degradation started. Spectrolab provided I-V curves for each array which showed them to be good, but damage could have occurred during packing, shipping or installation, rather than in the environment. In any case, if these arrays had been used on operational aids to navigation, the results would have been disastrous.

Table 3.1-2. Spectrolab Module Output
(Normalized to 100 mW/cm^2 @ 25°C)

Module Type	# of Modules	Average Output (mA)	Std Deviation (mA)
Long/flexible	30	244	11
Long/stiff	45	158	85
Short/flexible	30	245	14
Short/stiff	12	220	62

Examination of Table 3.1-1, the output of the Centralab arrays, shows their output has been quite consistent, but the failure mode of the Centralab arrays is very different. Month after month, their output is consistent and high until, as has happened with three of 25, they fail completely and without warning. The failure has been one of the inter-module connecting wire failing at the point where all of the modules are connected together. This point is in a cavity beneath one of the modules where the wires are soldered to terminals which pass through the aluminum base-plate to the external connector box. The failure is caused by water entering this cavity area and corroding the terminal lug/wire. Water can enter as the module "breathes" through incomplete seals at one of four places; the gasket to cover glass seal, the gasket to base-plate seal, the point where the wires from other modules penetrate the gasket and the places where the terminals penetrate the base-plate.

The first failure occurred in September 1974 and the next two were discovered while taking I-V curves in June 1975. A review of the daily solar summaries indicated that both had gone from full output to zero in about three days. Inspection revealed water and corrosion beneath the connection module. With the realization that we might have a serious problem developing, it was decided to inspect two other arrays which showed small drops in output. The cavity beneath both connection modules was full of water but there were only traces of corrosion on the terminals, not enough to cause a reduction in output. The water may not have been present long or some protection may have been added by some of the RTV sealing compound that was found to cover most of the lug.

It may be possible to protect the connections with a coating even if the water does get into the cavity. After inspection, all modules were repaired, resealed, and the arrays returned to the test.

Further study of the problem revealed that by using a high intensity light, it was possible to look between the rows of cells and see the terminals beneath clearly enough to determine if corrosion had begun. Upon inspecting the remaining arrays, two more were found with advanced corrosion that would have led to early failure. They were also repaired and returned to the test. To date, because of failure or inspection for other reasons we have lifted modules on eight Centralab arrays. All but one had water and most had corrosion in the connection cavity. Water was also found under other modules, although not nearly as often as under the connection module, but there are no contacts to corrode, and no damage is yet apparent.

3.2 Voltage Regulators

Since typical solar arrays can generate voltages in excess of battery full charge voltages, it may very well be necessary to incorporate a voltage regulator in the design to prevent damage to the battery or reduce loss of the water in the electrolyte. In order to test the validity of this argument each array manufacturer supplied some systems with voltage regulators of their choice. In the test were nine Centralab systems with non-adjustable regulators of the series type and nine Spectrolab systems with adjustable shunt type voltage regulators. Spectrolab recommended a different maximum voltage for each of the three battery types while Centralab recommended the same voltage for all. The voltage regulators were mounted in the battery boxes on the roof. After the initial check, it was not intended to take voltage regulator measurements since it was thought that the design and manufacturer of voltage regulators was so state-of-the-art that no problems would be encountered. This assumption proved incorrect. Daily summaries indicated that some batteries were not receiving a sufficient portion of the array output. This was traced to the adjustable voltage regulators that had drifted lower than their original settings. After several readjustments during the first few months, it was decided to stop making adjustments, measure the voltage periodically and observe the effect of any drift on the systems. The procedure for measuring the regulating voltage was to replace the battery with a 270 Ω resistor (per Spectrolab's recommendation) and read the voltage across it. The array output voltage was also read to make certain that it was well above the regulating point. Data from the measurements are presented in Table 3.2-1. The battery in System #6 reached 0 percent capacity in early November 1974 due to a faulty voltage regulator. Two other systems in the table failed to survive the winter because the regulated voltage drifted too low to allow the batteries to be charged. One Spectrolab voltage regulator failed completely in July 1974, shortly after the system was installed and it was replaced.

The variance in the voltage from the Spectrolab voltage regulators, and the poor arrays, made evaluation of the effectiveness of the voltage regulator very difficult. However, with six of the Centralab systems using 26Ah Wisco DA-2-1 liquid electrolyte batteries the differences between regulated and unregulated systems were marked. Some of the data are shown in Table 3.2.2.

TABLE 3.2-1
VOLTAGE REGULATOR PERFORMANCE

Systems 1 through 9 are Spectrolab (Shunt Type; Adjustable)

Systems 10 through 18 are Centralab (Series Type; non-Adjustable)

# #	BATTERY TYPE	ARRAY MFG DESIGN VOLTAGE	NOV 26 1974	JAN 22 1975	JAN 23 1975	FEB 3 1975	APR 1 1975
1	GLOBE	14.4V	13.5	13.1	12.9	13.0	14.8
2	"	14.4	14.5	14.2	14.2	14.2	13.2
3	"	14.4	14.5	14.3	14.4	14.4	14.4
4	WISCO	13.5	12.7	9.4	10.8	10.6	--
5	"	13.5	13.5	15.7	12.6	8.4	--
6	270 Ω SHUNT	13.5	13.1	12.9	13.0	13.0	14.4
7	GATES	15.4	15.3	14.9	14.9	14.9	15.1
8	"	15.4	16.3	14.6	15.9	15.9	16.0
9	"	15.4	15.6	15.2	15.4	15.3	15.1
10	"	14.2	13.7	13.6	13.8	13.7	13.9
11	"		13.9	13.7	13.8	13.7	14.0
12	"		13.9	13.7	13.8	13.7	14.1
13	GLOBE		13.9	13.7	13.9	13.8	14.0
14	"		14.0	13.9	13.9	13.9	14.2
15	"		13.8	13.7	14.0	13.9	14.2
16	WISCO		13.7	13.7	13.9	13.7	14.1
17	"		13.9	--	13.8	13.8	14.1
18	"		13.9	--	13.9	13.9	14.2

Table 3.2-2. Water Use in Wisco DA-2-1 Batteries

System	Voltage Regulation	Battery Box Color	Lamp Size	Total ml water added 5-74 to 7-75
16	Yes	White	.25	188
17	Yes	Gray	.55	88
18	Yes	Gray	.55	112
49	No	White	.25	1390
50	No	Gray	.55	1028
51	No	Gray	.55	975

The reserve electrolyte amounts to 160ml @ 95mm above the plates for each Wisco DA-2-1 battery, so without question the unregulated systems would not survive a year of unattended operation while the regulated ones probably would. There has been a suggestion that the ratio of array size to battery size can determine the need for a voltage regulator. The 100Ah Wisco DD-3-3 batteries on test were used with Spectrolab systems and while the data shows higher water usage with an unregulated system; it was impossible, because of erratic array and voltage regulator performance, to determine if battery size was a factor. Table 3.2-2 also indicates that, as expected, a smaller load results in more overcharge and greater water usage.

Whether a voltage regulator will in fact be required on the final system design has not yet been determined. However, the research to date indicates for some systems a regulator is required. The addition of a regulator adds (1) increased costs, (2) increased complexity, (3) increased energy loss, and (4) another item to fail hence reducing reliability. However, in terms of the entire system, all these additions can be small. The goal is long system life and to allow a battery to survive the overcharge of many summers. The addition of a regulator will probably be cheap insurance.

Due to the nature of the application, with a low-power constant-current source charging a battery which exhibits a direct relationship between state of charge and terminal voltage, it appears that a zener diode regulator may suffice. The problems with such a simple, one-element voltage regulator are all within the present state-of-the-art as follows:

a. Reliability - estimated to be measured in years

b. Cost - less than $5 per diode in quantities of 1000 or more

c. Workmanship - not a factor; however, diodes may be x-ray tested prior to shipment for around $0.25 each

d. Installation considerations - reasonably easy, with only a minimum heat sink necesssay

e. Power rating - 50-watt units are available at the cost cited; prospective systems would have power outputs of no more than 10-20 watts

f. Aging - insignificant

A thorough literature search disclosed few applications of zener diodes as herein proposed. This is undoubtedly due to the power limitations of zener diodes presently available; virtually any battery charger is capable of producing more than the fifty watts a zener diode is capable of dissipating. However, the application under study is unique in that solar cell arrays of the size contemplated produce less than this relatively low maximum device rating. In fact, the only factors presently identifiable as being possible problem areas are those of sample-to-sample tolerance and temperature stability. Consequently, since no data is available upon which to base further recommendations, further research and testing is indicated to evaluate the zener as a voltage regulator.

If zener diodes are used, the configuration proposed for eventual adoption is shown below:

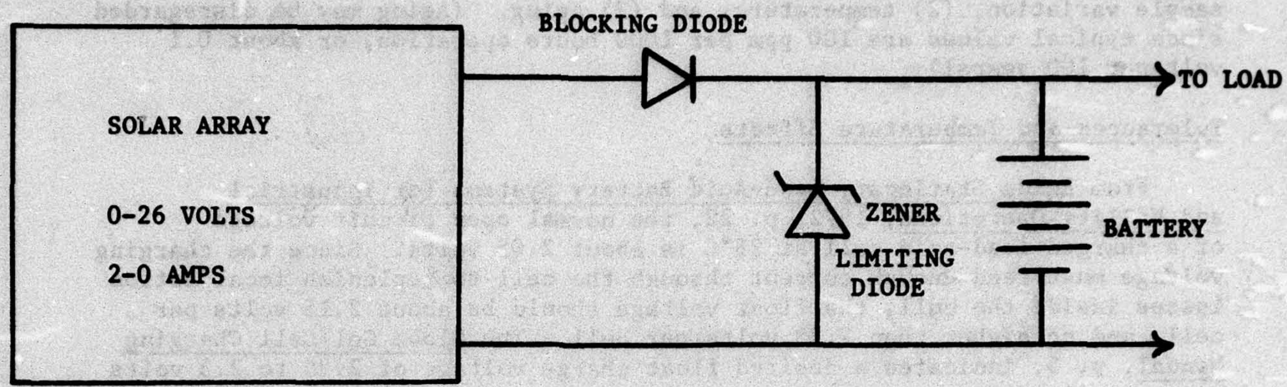


FIGURE 3.2-1 - PROPOSED CONFIGURATION WITH ZENER DIODE

The basis for this proposal is contained in the current-voltage relationship of the zener diode itself.

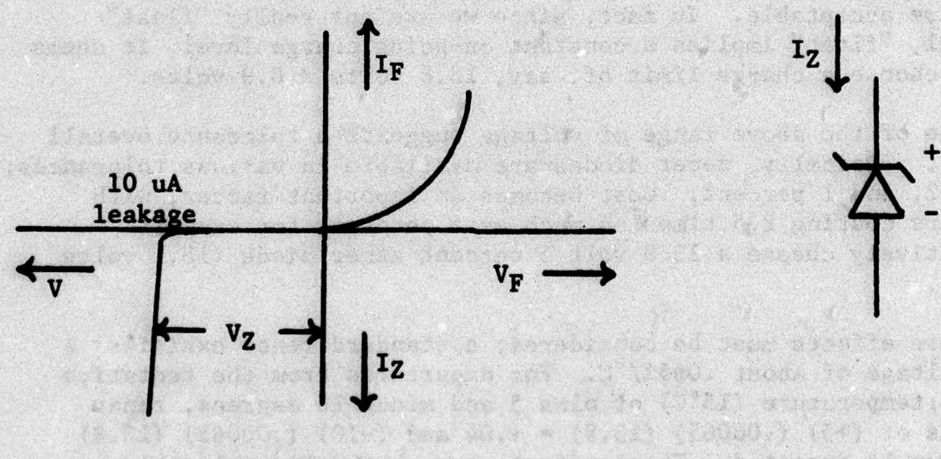


FIGURE 3.2.2 - CURRENT-VOLTAGE RELATIONSHIP FOR ZENER DIODE

As I_Z increases, V increases only slightly, providing automatic control. To achieve a certain battery voltage, merely select the zener such that:

a. V for I max, the maximum solar array output expected, is in accordance with the battery manufacturer's recommended float charge voltage. Since full charge is only expected during summer peaks of high array output, the "worst case" of possible overcharge takes place under such conditions. For currents less than I max, V is lower, but only slightly so (perhaps 0.1 volt).

b. The device voltage variation tolerance is acceptable under all conditions expected. Factors affecting zener breakdown voltage are (1) sample variation, (2) temperature, and (3) aging. (Aging may be disregarded since typical values are 100 ppm per 1000 hours operation, or about 0.1 volt per 100 years!)

Tolerances and Temperature Effects

From Exide Stationary Lead-Acid Battery Systems for Industrial and Utility Operations, 1972, p. 22, the normal open circuit voltage of a charged lead-acid cell at 25°C is about 2.05 volts. Since the charging voltage must feed enough current through the cell to replenish local action losses inside the cell, the float voltage should be about 2.15 volts per cell, and no higher than 2.33 volts per cell. The Globe Gel/Cell Charging Manual, p. 5, indicates a desired float charge voltage of 2.25 to 2.3 volts per cell (at 25°C). At a somewhat lower temperature of 15°C, as might be expected in a buoy pocket, the desired voltage range is 2.3 to 2.35. So the final voltage selected will depend on the type of battery(s) and environmental conditions.

Summarizing, for an assumed buoy operating temperature of 15°C (expected range might be 5-20°C), float voltage should be no higher than 2.35, and no lower than about 2.15, volts per cell. Corresponding battery voltages would be 6 x 2.35 = 14.1 and 6 x 2.15 = 12.9 volts.

Experience gained to date, and the fact overcharge may be expected only during several of the summer months, suggests that higher values of float charge are acceptable. In fact, since we are not really "float" charging at all, "float" implies a constant on-going charge level, it seems reasonable to choose a charge limit of, say, 13.8 volts ± 0.9 volts.

Acceptance of the above range of voltage suggests a tolerance overall of 6.5 percent. Typically, zener diodes are available in various tolerances; 20, 10, 5, 3, 2, and 1 percent. Cost becomes an important factor, with 1 percent zeners costing 2.5 times as much as 5 percent, for example. We would tentatively choose a 13.8 volt 5 percent zener diode (13.1 volts to 14.5 volts).

Temperature effects must be considered; a standard zener exhibits a change in voltage of about .065%/°C. For departures from the tentative design ambient temperature (15°C) of plus 5 and minus 10 degrees, zener voltage changes of (+5) (.00065) (13.8) = +.04 and (-10) (.00065) (13.8) = -.09 volts may be expected. These effects are obviously negligible. Note, however, that if the zener diode is mounted above the waterline in the buoy, or in any application which does not enjoy the relatively stable temperature of the water, temperatures of around -20°C to 50°C may be expected. The typical zener diode would exhibit voltage fluctuations at temperatures of +25° and -45° about a design temperature of 25°C:

$$\Delta V = (+25)\ (.00065)\ (13.8) = +.22$$
$$\Delta V = (-45)\ (.00065)\ (13.8) = -.40$$

and these effects may no longer be negligible. Assuming worst case sample tolerances of 5 percent, or 0.69 volts, diodes of from 13.8 - .69 =

13.11 v. to 13.8 + .69 = 14.49 v. might be encountered. Summer voltages of 14.49 + .22 = 14.71 volts and winter voltages of 13.11 - .40 = 12.71 volts will occur. Whether these charge levels are acceptable remains to be seen; testing may be in order. For example, at the higher temperature, which gives rise to the higher zener voltage, battery manufacturers recommend somewhat <u>lower</u> cell voltages than at lower temperatures. Furthermore, it may be that the lower voltage (12.71 volts) will result in undercharging of the battery during winter months. If a problem with voltage levels does exist, overcoming it is simple - but expensive. Several solutions exist:

a. Use temperature-compensated zener diodes, which exhibit only .01%/°C variation:

$$\Delta V = (+25)\ (.0001)\ (13.8) = +\ .03$$
$$\Delta V = (-45)\ (.0001)\ (13.8) = -\ .06$$

for net charge voltages (with a 5 percent 13.8 volt zener) of from 14.49 + .04 = 14.53 to 13.11 -.06 = 13.05 volts. Cost: double the non-temperature compensated diode.

b. Use 2 percent zener diodes: (.02) 13.8 = 0.28v; the voltage range due to sample tolerance is 13.9 -.28 = 13.52v. to 13.8 + .28 = 14.08v. and, with the temperature effects (.065%/°C), the worst case overall range is 13.52 -.40 -13.1v. to 14.08 + .22 = 14.3v. Cost: Again, double the non-temperature compensated 5 percent zener.

c. Use larger batteries in colder climates to allow for the possible reduction of winter charge.

d. Select diodes for cold/hot climates by sorting. That is, sort the "standard" diodes to find those on the high/low side of the 5 percent tolerance.

Tolerance variations among zener diodes, both standard and temperature compensated,.and the resulting effects on worst case summer and winter charge levels are tabulated in Table 3.2-3. Cost data is also included (on the basis of one thousand units). While the actual costs will undoubtedly change the relative value among them should remain constant.

TABLE 3.2-3
ZENER DIODE COST COMPARISON

	TOLERANCE OF DIODE	TEMP COEFF	SUMMER WORST CASE (50°C)	WINTER WORST CASE (-20°C)	UNIT COST
STANDARD	10%	0.65%/°C	15.40 V.	12.02 V.	$2.23
	5%	0.65%/°C	14.71	12.71	3.10
	3%	0.65%/°C	14.44	12.98	4.65
	2%	0.65%/°C	14.30	13.12	5.58
	1%	0.65%/°C	14.16	13.26	7.75
TEMP COMPENSATED	10%	0.01%/°C	15.21 V.	12.36 V.	$4.45
	5%	0.01%/°C	14.52	13.05	6.20
	3%	0.01%/°C	14.25	13.32	9.30
	2%	0.01%/°C	14.11	13.46	11.16
	1%	0.01%/°C	13.97	13.60	15.50

3.3 Batteries

The primary concern as to batteries is the life of the battery and the changes, if any, of the capacity during that life. Items of secondary concern are charge efficiency, self-discharge, maintenance requirements, the level of voltage required for charging, temperature effects, etc. This section discusses the data from both the operation on the roof and from special laboratory tests.

The first question to ask when receiving a "new" battery from a manufacturer is does the battery meet the advertised specifications? Or put another way, is it a good battery? To determine this a program of measuring the capacity of each new battery was undertaken. Table 3.3-1 lists the manufacturer-supplied specifications for charging/discharging the four different battery types. Each battery type presented unique difficulties in measuring both initial capacity and the dependence of remaining capacity on voltage and/or specific gravity. These problems and their final solutions are discussed separately later.

TABLE 3.3-1
BATTERY MANUFACTURER RECOMMENDATIONS FOR
CHARGE/DISCHARGE TECHNIQUES AT ROOM TEMPERATURE

Battery Type	Charge Technique	Discharge Technique
Globe - 12V, 20Ah	14.7 volts, current limited to 3A for 24 hours or until current drops to 0.3A	1.0 amperes until terminal voltage* = 10.5
Gates - 12V, 60Ah	14.7 volts current limited to 10A	6.0 amperes to terminal voltage* = 10.2
Wisco - 12V, 100Ah	15.5 volts current limited to 5A for 48 hours or until S.G. remains stationery for about 3 hours	0.25A until terminal voltage* = 10.2 or until specific gravity = 1.120
Wisco - 12V, 26Ah	Same as for 100Ah except current limited to 1A	0.1A until terminal voltage* = 10.2 or S.G. = 1.100

*closed circuit voltage in all cases

A battery was rejected as bad if its initial capacity measured less than 80 percent of nominal capacity. The nominal capacity depends in each case on the actual current drain; it is well documented in the literature that the apparent battery capacity drops as the current increases. This fact was used to accelerate the test program. A normalizing factor was determined in each case for a higher than "normal" current drain. In some cases the manufacturer supplied this information (e.g. for the Gel Cell). However, whether supplied or not, a normalization factor was experimentally determined for each combination of battery type and "larger-than-normal" drain. The same basic technique was used in all cases. It consisted of:

a. Discharging a fully charged test battery at "normal" rate and recording capacity.

b. Recharging same battery, and

c. Discharging again but at a higher rate.

Comparing the capacity recorded under a and c provides the desired normalization factor. It is recognized that these capacities will vary from charge to charge and that this was too small a sample to be statistically correct. However, the prime use was to determine if the battery was acceptable as a "new" battery or not. In addition to accrediting each battery and recording its normalized initial capacity, careful measurements were made of battery voltage vs. removed Ah during the discharge cycle, and, where appropriate, of the corresponding specific gravity (S.G.) corrected to 80°F. Since different batteries were in storage at the R&D Center for times varying from one to six months, a standard procedure adopted was to recharge each battery just before measuring capacity. The inventory of batteries tested in this program were (24) 100Ah, 6 Volt Wisco; (54) 26Ah, 2.1 Volt Wisco; (13) 60AH, 12 Volt Gates; (54) 5Ah, 12 Volt Gates and (54) 20Ah 12 Volt Globe (Gel-Cell). This inventory covered the needs for 66 systems.

12 Volt 20Ah Globe

This was the only type that presented no particular difficulties in measuring initial capacity. Accelerated test discharge rate adopted was 2.5 amperes, capacity normalizing factor was 1.1. Five units were rejected because: one leaked electrolyte, two exhibited corroded terminals, and two would not accept charge.

6 Volt 100Ah Wisco

There were no rejected units. The accelerated test discharge rate adopted was 2.5A; capacity normalizing factor was 1.3. The principal problem was in a tendency of the battery to "percolate" as it approached the end of a charging cycle. "Percolation" is the bubbling over of electrolyte past the battery cap. It is probably caused by the lowered charge efficiency causing a portion of the charging current to electrolyze the water. The released H_2 and O_2 temporarily trapped between plates displaces electrolyte causing the level to rise. Eventually the bubbles break free to the surface resulting in a sudden drop in liquid level. There are several solutions to this problem. A smaller charging current

can be used, a lesser total amount of electrolyte can be used, or an "expansion chamber" battery cap can be used. The latter is a hollow plastic tube several inches long provided with a gasket and thread to replace the standard cap. Any displaced electrolyte creeps into this tube during charging and later falls back again without any net loss of liquid. Expansion chambers were used for all laboratory check-out procedures. The summertime charging currents experienced in actual (rooftop) systems are less than those used in the laboratory and ordinary battery caps have been adequate. Individual records of Ah removed vs. voltage under load and vs. S.G. have indicated that the S.G. is an excellent, reliable, and rapid method of measuring the remaining capacity. In each case, the S.G. of a single cell in each 6 volt battery was monitored; it was assumed that the S.G. of the other two cells were in reasonable agreement.

2.1 Volt, 26Ah Wisco

Seven units were rejected; one had a broken case and six had too low an initial capacity. The latter ranged from 58 percent to 80 percent of stated capacity. Accelerated test discharge rate adopted was 1A; capacity normalizing factor was 1.3. This species proved very troublesome. The battery has insufficient headroom between the top of the plates and the underside of the case. This resulted in excessive percolation effects even at the lower rooftop operational rates. All systems installations had the conventional caps permanently replaced with expansion-chamber caps. No hydrolator caps are available for this size battery. The insufficient headroom led in turn to other problems. These batteries do not hold enough liquid to float the indicator in a conventional hydrometer. Consequently, smaller volume, less accurate hydrometers had to be used.

12 Volt, 60Ah Gates

Two units were rejected due to overheating and inability to accept charge. The manufacturer-recommended discharge rates were adequately large and capacity normalization techniques were not used. We experienced large problems in testing these batteries such as non-reproducible capacity, overheating, and a high individual cell failure rate. Overheating is especially serious with this battery because of a tendency to "thermal runaway." This occurs when increased temperatures lower the internal resistance and increase the charge current. This results in self-destruction if not halted and is related to the design of placing 12 batteries in parallel so they are all presented with the same current-limited voltage. The entire battery is, in a sense, in a state of nonstable equilibrium due to the competition for charging current among all the strings. Another peculiarity of this battery is that the internal resistance of each cell (2.1 volt, 5Ah) is very small due to the internal construction. The manufacturer has therefore provided external 10 ampere fuses, one per parallel string.

At our request, a representative from Gates visited us and advised us on how to handle these problems. He stated that the initial principal reason for the high individual cell failure rate was the inadequate charge technique employed. A revised charging technique was suggested and a technique was proposed to "restore" or "recondition" a battery which showed poor

performance. The latter technique consisted of disassembling the battery and reassembling into a 151 Volt, 5Ah battery using (72) 2.1 volt cells in series. A bootstrap charging technique (to last a week!) was then recommended in order to insure that the least charged cell had been brought up to charge. At the end of a week, we were to disassemble and then reassemble into the original 12 x 6 parallel-series configuration. The reconditioning technique was never adopted since the high incidence of cell failure diminished once we adopted the revised initial charging technique per Table 3.3-1. Performance of this battery will be closely observed in the laboratory experiment since there is no "control" over the charging current delivered to the battery each day.

12 Volt, 30Ah Gates

This battery is identical to the 60Ah Gates except that there are only 6 parallel strings of 12 volt, 5Ah batteries employed. There was one failure (wouldn't accept charge).

Thus during the initial capacity tests a total of 15 batteries out of 66 systems were rejected as unsatisfactory for service. This high failure rate is not unusual. In a separate battery evaluation a total of 113 batteries were procured from the same manufacturers. The results of initial capacity check are as follows:

	Gates	Globe-Union	Wisco
Number failed to deliver 80% rated capacity	3	5	1
% rejected	7	14	3

What this undoubtedly means is that if secondary batteries are used on aids the Coast Guard will have to cycle each battery before placing it in service.

Water Usage

The loss of water from the liquid electrolyte batteries through evaporation or hydrolysis was one of our main concerns. The cost of maintenance for aids to navigation exceeds the cost of the aids themselves since a ship must visit an aid for the inspection. The use of a solar power unit versus the current 350-pound air-depolarized battery will mean a small ship could replace failed power units but the fewer trips scheduled, the greater the savings.

The water use in the Wisco DA-2-1 batteries was previously discussed in the voltage regulation section. Those small, 26Ah, batteries would require yearly maintenance to add water even with voltage regulation. For this and other reasons these batteries were removed from the test and are no longer being considered.

The Wisco DD-3-3 battery at 100Ah represents a different class of battery. This larger battery is better suited for the level of overcharge current that occurs during the summer. At the start of the rooftop evaluation the cells of these batteries were closed by three different types of caps:

(1) A standard vented cap

(2) a "hydrocap" provided by Spectrolab

(3) A "hydro-catylator" cap purchased from the Hydro-Catylator Corporation, Hialeah, Florida. The latter two caps are products which are designed to limit water loss by using a catalyst to recombine the hydrogen and oxygen generated during over charge into water. The results of the first summer's operation are shown in Table 3.3-2.

TABLE 3.3-2
WATER USAGE FOR WISCO DD-3-3 BATTERIES

SYSTEM	AVERAGE ml WATER PER CELL ADDED IN PERIOD INDICATED				VOLTAGE REGULATION	BATTERY BOX COLOR	LAMP LOAD (AMPERES)
	JUNE 1974 TO JANUARY 1975		JUNE 1974 TO JANUARY 1975				
	HY	STD	hy	STD			
4	27	36	18	27	YES	WHITE	0.55
5	0	0	0	0	YES	GRAY	0.77
6	9	0	18	9	YES	GRAY	1.15
22	18	54	36	54	NO	WHITE	0.55
23	36	36	54	45	NO	GRAY	0.55
24	36	36	54	63	NO	GRAY	0.77
25	9	36	18	54	NO	GRAY	0.77
26	9	36	18	27	NO	GRAY	0.77
27	9	36	18	36	NO	GRAY	0.77
29	18	54	0	45	NO	GRAY	0.77
30	18	163	18	27	NO	GRAY	1.15

hy - hydrocap
HY - hydro-catylator cap

Reserve electrolyte (above plates) is 240 ml/cell

Examination of the data shows the "hydro" type caps did reduce water loss. However, using a voltage regulator resulted in an equal or superior reduction in water loss. In fact, the largest water loss was 63 ml and since the reserve electrolyte is 240 ml this cell could last three or four years without requiring the addition of water. The high water use of 163ml in system #30 occurred in a cell that had a hole cut in it for the insertion of a remote reading thermometer.

No water has been added to any battery since January 1975. The batteries operated satisfactorily through the summer of 1975, and from the current electrolyte levels it appears the batteries will continue to operate satisfactorily without adding water for at least two more years.

Capacity Checks

A key to the evaluation of system performance is a determination of the capacity remaining in the storage battery at any time by in situ methods. For the liquid electrolyte battery the capacity can be determined from a measurement of the specific gravity of the electrolyte in each cell. We have found the specific gravity measurement to be an excellent indication of capacity except where some other failure has occurred. That is, should a failure such as an increase in resistance at a connection due to corrosion occur, the battery may not be able to deliver the capacity indicated by the specific gravity measurement.

The determination of the capacity of the sealed batteries is another matter. Here the specific gravity cannot be measured and generally we do not want to remove a battery from service to measure the capacity by discharge measurements. Most manufacturers provide a voltage versus capacity curve for their batteries. All three battery manufacturers had such curves in their literature but they were either for discharge rates larger than we use or the discharge rate was not specified. We attempted to generate voltage under load versus capacity curves for the batteries by measuring several batteries under our discharge conditions. We have used this data to determine the capacity of the sealed batteries when checking our system design (see Section 4.1). By actually discharging a sample of the batteries at different times of the year we have been able to determine the accuracy of the voltage versus capacity method. It is accurate only if no failures or degradation has occurred to any of the cells. The Gates and Globe batteries consist of parallel and series strings of individual cells. A failure in one parallel string may or may not affect the voltage depending upon the exact nature of the failure.

The results of one check of six batteries in May of 1975 is presented in Table 3.3-3. The data on system 32 is most interesting. This Gates battery is composed of 72 cells, 12 parallel strings of 6 series connected cells. The voltage under load indicated that the battery was fully charged - 98 percent capacity. Upon discharge the battery delivered only 47Ah, or 78 percent of rated capacity. Further testing revealed some of the parallel strings had failed and the battery would only deliver 47.8Ah.

It may be possible to develop a technique of determining the capacity of the sealed batteries by subjecting them to a high current discharge for a short period and analyzing either the rate of change of the voltage or the end voltage. If this type battery is selected for operation such a project will be undertaken.

Battery Failures

The number of battery failures during the first two years of service has been less than expected. A summary is as follows:

Wisco 26Ah - All six batteries were removed from test because of high water use. No actual failures occurred.

Wisco 100Ah - Three out of twelve failed. Two failures were due to corrosion of the wire at the positive terminal - these were repaired. The third failure was a crack in the case of one cell - the cause could not be determined and it could not be repaired.

Globe - Two failures out of 14 batteries. Both failures occurred to batteries where the positive terminal corroded completely away.

Gates - No failures out of 21 batteries.

We have had other battery failures caused by either system (panel) failures or insufficient charging due to the original selection of panel and load. For instance, system 37 had a Gates 60Ah battery and a 0.77 amp lamp. This system was designed so the battery would drop to 0 percent capacity during the winter. On 12 February 1975 the voltage under load dropped below 11 volts and from 26 February to 23 April the voltage remained below nine volts. While some batteries in almost identical conditions recovered in the early summer, this battery would not accept any charge. The abuse of continually loading the battery every night when it was already completely discharged apparently damaged the cells.

3.4 Miscellaneous

Cracks have developed in some of the exposed cabling leading from the battery box to the 1/10 ohm shunts (auto-coulometers) and in cabling from the panels to battery boxes. The box-to-shunt cables were provided by R&DC and are the "outdoor portable power cable" type NS Number 9Z6145-191-3614. This is weather resistant but not UV resistant. In most, but not all cases, cracking occurred where severe bends were used; i.e., less than about a 2" radius. The box-to-panel cables were provided by the two contractors, Spectrolab and Centralab. None of the Centralab cables have developed cracks. About half of the Spectrolab cables have developed cracks. In no case has system operation been affected. In cases where the boxes have been painted, some paint has gotten on the cable and caused additional deterioration. Specifying type SO cable and keeping the paint off should solve this problem.

TABLE 3.3-3
LABORATORY CAPACITY CHECKS OF SIX SEALED BATTERIES

SYSTEM	BATTERY TYPE	INDIVIDUAL BATTERY NO.	REMAINING CAPACITY~1 MAY 1975		MAXIMUM CAPACITY (Ah)		% CHANGE IN MAX.CAP.
			PREDICTED FROM "V_L"	MEASURED IN LAB	MAY 1974	MAY 1975	
2	GL-60	8 15 22	34% of 60.0 20.4Ah	4.0 Ah 5.25 7.2 Σ = 16.45 Ah	22.4 18.5 18.6 Σ = 59.5	19.5 19.8 20 Σ = 59.3	0%
8	GA-60		12% of 60.0 7.2Ah	6.5 Ah	52.5	57.6	+10%
32	GA-60		98% of 60.0 58.8Ah	47.1 Ah	61.9	47.8	-23%
43	GA-30		100% of 30.0 30.0Ah	25.2 Ah	24.9	25.2	+1%
44	GL-40	16 17	90% of 40.0 36.0Ah	20.3 Ah 12.5 Σ = 32.8 Ah	21.6Ah 20.5 Σ=42.1Ah	21.6Ah 17.3 Σ=38.9Ah	-8%
52	GL-40	31 46	100% of 40.0 40.0Ah	22.6 Ah 18.0 Σ = 40.6 Ah	16.0 Ah 21.0 Σ = 37 Ah	22.6 Ah 18.0 Σ = 40.6	+10%

Extensive external rusting has occurred on all battery boxes. Minor rusting has occurred in the inside of all battery boxes. Thus far, all rust has been only a cosmetic problem. All of the boxes with the liquid electrolyte batteries have more corrosion than those with sealed batteries, with the unregulated systems being the worst - even with a sealed battery, the corrosion is enough to warrant special materials, fiberglass or stainless steel, for long-term operation.

4.0 DESIGN AND NEW AREAS

System design information can also be obtained from the test in addition to data on component performance. There are also several new areas in the test.

4.1 Design

The design of a solar-powered system appears to be quite straightforward from the point of being able to identify the major factors that affect system operation. These factors are (1) energy production including expected insolation, array conversion efficiency and transmission losses, (2) energy storage including battery storage efficiency, battery size and long-term loss of capacity, (3) energy consumption which includes the load profile and expected hours of darkness, and (4) special considerations such as safety factors, minimum voltage requirements, size of reserve, and definition of unsatisfactory operation. From the variation in the designs of Centralab and Spectrolab in 1972 (Section 1.1), it was apparent that research into these factors was required in order to optimize the system. None of these factors are simple. Consider the load in the aids to navigation case. The light on a buoy does not present a nice steady load to the system. Not only is it flashing (for identification purposes) but, since it operates only during the nighttime, it operates longer during the winter. Thus this is one parameter to be considered in selecting the size of the battery required for sufficient storage of energy. We must store enough energy to keep the aid in operation as the system is subjected to the environment year after year.

Recognizing that our estimates of the parameters could be in error, we divided the loads into three classes - one sized to exactly meet the estimates and one both smaller and larger than the estimate. The division among the 54 rooftop systems was 13 below, 8 above, and 32 at the design level. As the first year passed we found we had been overly conservative.

The design, or calculation, of the electrical load for the laboratory solar power units was based on the premise that the discharge of the battery in an "ideal" unit would vary between 0 and 80 percent during the year. That is, in the summer the battery would reach full charge and in the winter the battery would reach a low of 20 percent capacity remaining. This low point of 20 percent capacity may be changed depending on the results of the battery tests and operational considerations.

The first load design was based on the below listed factors:

Local insolation - The average insolation for each month was used. A failure could occur if the insolation remained below average for a long period but a review of the measurements for the past 27 years revealed that for the period there were no two months in a row with minimum insolation.

Transmission of the cover glass - Dirt, bird foulings, etc., will reduce the transmission of the cover glass. No data was found on this transmission except comments such as the panels are kept relatively clean by rain. A transmission of 0.76 was used.

Degradation of solar panel - It is assumed no long-term degradation of the glass or solar cell will occur.

Loss from regulator - It is assumed the regulator circuit will operate only when the battery is near full charge so no loss is considered.

Charge storage efficiency - This factor is difficult to estimate since it depends on charge rate, battery capacity, temperature, etc. An efficiency of 80 percent is used. This may appear high, but the time when efficiency is the most important is when the capacity is reduced and at that time the efficiency is increased. As the battery tests proceed, this factor will be better determined.

Self-discharge of batteries - This factor is small (< 1% per month) for these lead-acid batteries and is considered negligible.

Insolation

The start of the design of any solar system has to be the amount of energy available. Insolation measurements have been made in many places for years, primarily by the Government, and are available in various publications. We have used the Climatic Atlas of the United States which is available through the U. S. Government Printing Office, and the University of Wisconsin "World Distribution of Radiation."

However, no yearly insolation records are available for Groton so it was decided to use data from Newport, RI, to predict system operation for the following reasons:

a. Latitudes differ by only 11 minutes

b. Neither area has heavy industry

c. Both areas are on the southern New England coast

The values of insolation used were monthly averages for the years 1950 to 1961 as found in University of Wisconsin "World Distribution of Radiation" Report #21, page 50. The use of a monthly average might be questioned from two points: the period of time and the selection of an average versus a minimum or some other level. While insolation data on an hourly basis is available it did not appear fruitful to reduce the design to this small a basis. It was thought that any battery selected would probably have a storage capacity of enough energy to operate for two weeks to a month with no input, so this time frame seemed reasonable. This time frame also is long enough to reduce the spread in the monthly data from year to year. The use of an average is also satisfactory because of the battery storage. It is most probable that two or more "minimum" months would not occur in a row. In fact, a search of the records over a 27-year period at Newport showed no two months with minimum insolation occurring together.

It has been suggested that slight displacements (as little as 30 km) would result in such large changes in insolation that each location would require measurement. Figure 4.1-1 is a comparison of the insolation levels used in the original estimates, the levels measured at the R&D Center and

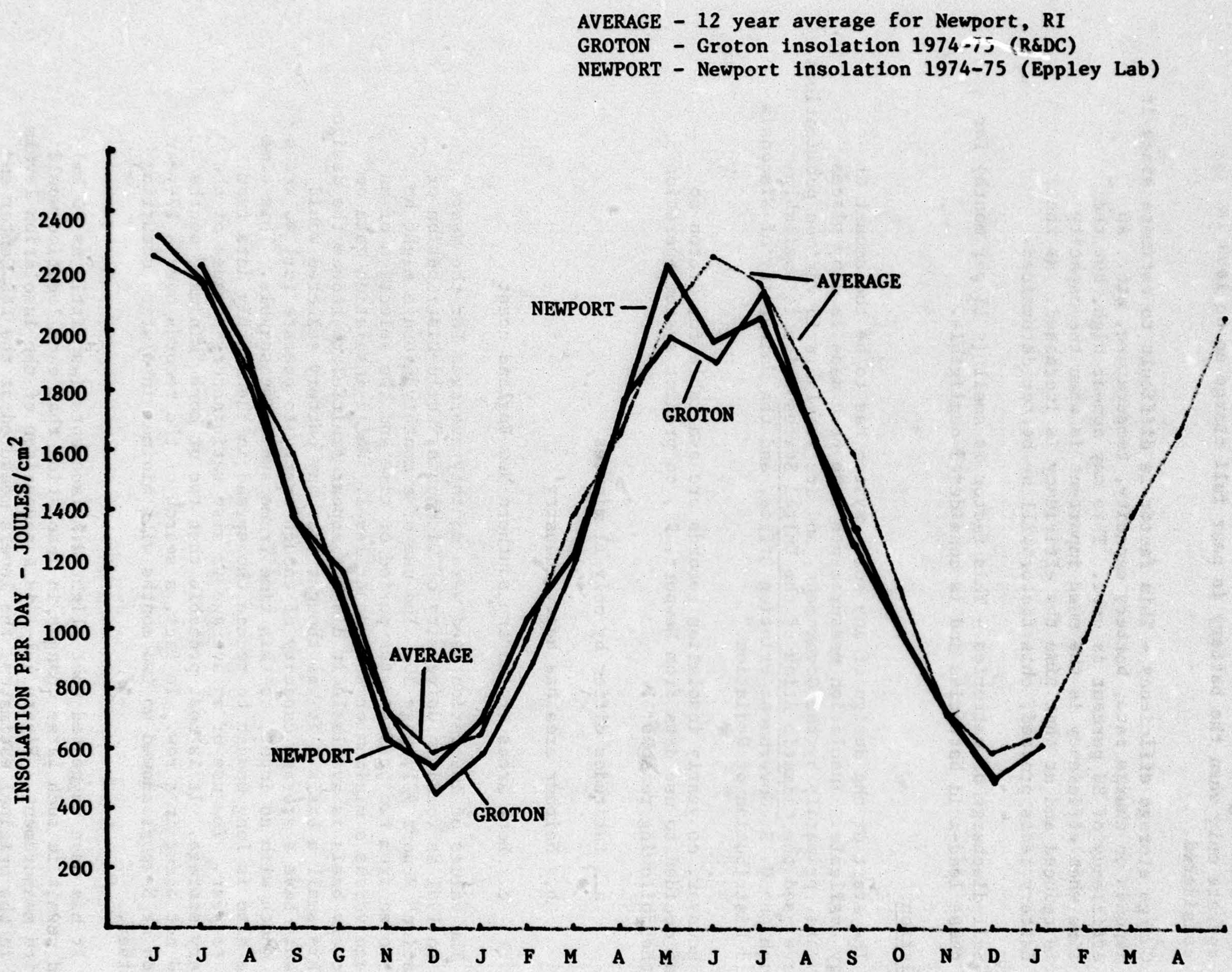


FIGURE 4.1-1 - COMPARISON OF INSOLATION LEVELS

the insolation levels measured in Newport by the Eppley Laboratory, Inc. Because of this excellent agreement there appears to be no reason to stop using Newport as a surrogate area for Groton. As an aside, there was also a prediction that solar arrays located on buoys would receive as much as 50 percent more insolation than a similar shore location by virtue of having a larger "sky" or by seeing a reflecting surface rather than an absorber when the buoy rocks. Part of the solar project included a small "buoy farm" of eight 6-foot diameter buoys equipped with solar powered units. The buoys are located in Long Island Sound about one kilometer from the rooftop facility. On one of the buoys is a standard cell and chart recorder used to measure insolation. The insolation levels recorded on the buoy agree with the roof measurements to such an extent that they can be used without correction if there is an instrumentation malfunction on the roof. The standard cell was calibrated through side-by-side operation with the pyranometer as described in Section 2.3.2. After it was placed on the buoy, the insolation measured was no different from that measured on the roof and can be used as a backup if there is an instrumentation malfunction on the roof.

Array Output and Losses

The amount of energy that a solar array can be expected to produce can be calculated from estimates of insolation, and by knowing the voltage at which the array will operate. For a lead-acid battery of 6 series cells, this voltage should range from about 12 to 14 volts when a regulator is used. Each solar array manufacturer supplies current-voltage (I-V) curves, at given irradiance levels and temperatures, with their arrays. All of our curves showed the output at 100 mW/cm^2. From these curves, the current at the desired/expected operating voltage is found. Accurate selection of this voltage point is less important if it falls in the horizontal portions of the curve where changes in current with voltage are small. Dividing the current by the irradiance level gives a value of amperes per mW/cm^2. Then, since all of the insolation data available is expressed in langleys, the conversion

$$1 \text{ langley} = 1.1622 \frac{\text{mW-hr}}{\text{cm}^2}$$

must be used. Multiplying this number by amperes per mW/cm^2, gives the array output in amp-hours per langley, at the operating voltage. For the project at the R&D Center we chose 12.5 as the voltage at which the batteries would be charging during the critical winter months. For unregulated systems, 13.0 is a better choice but we operate that portion of the curve that is fairly flat and the error is not great. Larger errors are introduced in the case of large numbers of systems, by the fact that all of the arrays differ slightly and the system must be designed around either an "average" or a "minimum" current at the operating voltage. For our arrays we use an average figure of 0.0077 Ah/langley.

After the first estimate of array output has been made, it must then be reduced by expected transmission losses. When we began in 1973, there was no information available that we felt applied directly to our problem, so we made some assumptions. The original estimates of transmission losses were:

a.	Dust, snow, water, ice	≈ 7%
b.	Bird droppings	≈ 3%
c.	Weathering, aging, degradation	≈ 7%
d.	Reflection	≈ 7%
	Total	24%

It has not been possible to measure each of these items individually, but by measuring the total array output at regular intervals throughout the test, we have come up with a total average loss of 5-6 percent. By cleaning the arrays, we have been able to measure directly, the amount of dust/dirt accumulation. On five Centralab arrays that had been weathered for over a year before cleaning, the greatest increase in output after cleaning was five percent, the smallest was 2.5 percent and the average was 3.5 percent. The snow and ice melt rapidly in the daytime and have had no measurable effect and should be even less of a problem on a tilted or moving array. Birds are no problem if proper bird spikes are on the arrays. We know this because an array with no bird spikes, on the buoy farm was quickly fouled, while others, with bird spikes, were not. Reflection losses are small and are included in the manipulations to convert insolation in langleys to energy available in amp-hours. The final loss, aging/degradation is the difference between the total and that due to dirt. This loss is permanent and may be on a per year basis and caused by scratching of the surface or U-V degradation. Our best estimate of transmission losses today are:

a.	Dirt, snow, water, ice	2-5%
b.	Bird droppings	0
c.	Weathering, aging (2 years)	1-3%
	Total	3-8%

The losses due to dirt are probably the most variable and should not be assumed to be 2-5 percent without further investigation. Tests performed for the Coast Guard by Spectrolab at their Sylmar, California, location show losses due to dirt of up to 35 percent.

Voltage Regulators

The analysis of how a voltage regulator affects system operation is complex and has not been included in our in-house design. Their efficiency varies with temperature, type of regulator, voltage setting, type of battery and state of charge. Coulometer measurements indicate that the series type regulators provided by Centralab are 85-95 percent efficient in the winter. Since many types of regulators could be used the inclusion of this loss will have to wait until the decision on which, if any, regulator is to be used.

Batteries

If the battery remains "healthy" the primary problem in predicting system performance is knowing how much of the array output is stored for later use. This storage efficiency, or more properly ampere-hour efficiency, is dependent on a great many factors (for a complete discussion see Storage Batteries by G. W. Vinal). There were many early guesses as to the efficiency, and a conservative value of 80 percent was decided upon. This was later revised to be 85 percent efficient up to 90 percent battery capacity and 50 percent efficient above 90 percent battery capacity. Today, after discussion with battery experts, in-house research, and data analysis, we feel that the charge storage efficiency is within the range of 98-99 percent for our application. The three charge storage efficiencies that we have used are shown in Figure 4.1-2.

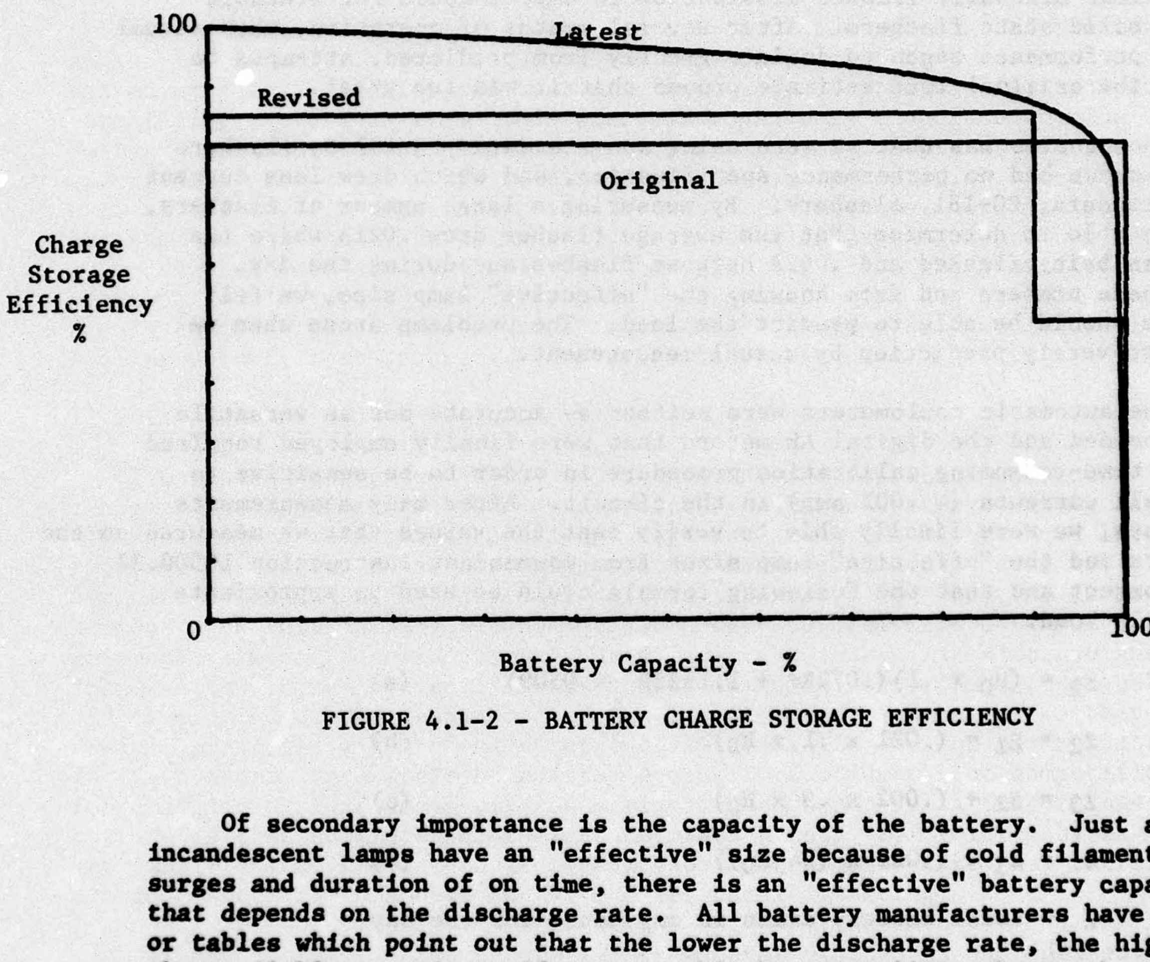


FIGURE 4.1-2 - BATTERY CHARGE STORAGE EFFICIENCY

Of secondary importance is the capacity of the battery. Just as incandescent lamps have an "effective" size because of cold filament current surges and duration of on time, there is an "effective" battery capacity that depends on the discharge rate. All battery manufacturers have curves or tables which point out that the lower the discharge rate, the higher the available capacity. Of course, this has some limits but we have found that the "nominal" battery rating, usually at the 8-hour or 20-hour discharge rate is effectively increased by 20 percent because we operate typically at the 300-1000 hour discharge rate.

The self-discharge rate of the batteries was addressed in the original estimates and was expected to be as high as 8 percent per month for some batteries. It has not been a noticeable problem, either because it is changed by the continuous charge-discharge operation of the battery or because it is masked and included in another factor such as increased capacity due to low discharge rates.

Load

Predicting the daily load on the system should have been the easiest and most exact part of the design. The lamps and flashers that were the loads for each system were controlled by a clock that was reset on the first of each month to adjust the load "on" time to be equal to the number of hours between sunset and sunrise for the 15th of that month. The "effective" lamp size for different flash duration times for various lamp sizes is tabulated in Commandant Instruction 10500.32 (Appendix B) which also lists the maximum allowable flasher dissipation in ampere-hours for standard CG-181 solid state flashers. After several months of operation, when actual system performance began to deviate greatly from predicted, attempts to verify the original load estimate proved that it was too great.

The problem was that we were using non-standard, CG-181-S, flashers for which we had no performance specification, and which drew less current than standard, CG-181, flashers. By measuring a large number of flashers, we were able to determine that the average flasher drew .021A while the lamp was being flashed and .002A between flashes and during the day. From these numbers and from knowing the "effective" lamp size, we felt that we should be able to predict the load. The problems arose when we tried to verify prediction by actual measurement.

The automatic coulometers were neither as accurate nor as versatile as we needed and the digital Ah meters that were finally employed required a very time-consuming calibration procedure in order to be sensitive to the small currents ($\approx$ .002 amp) in the circuit. After many measurements and tests, we were finally able to verify that the values that we measured on the flashers and the "effective" lamp sizes from Commandant Instruction 10500.32 were correct and that the following formula could be used to approximate the daily load.

$$Z_1 = (H_D \times .1)(.072R^2 + 1.1525R - .0309) \qquad \text{(a)}$$

$$Z_2 = Z_1 = (.021 \times .1 \times H_D) \qquad \text{(b)}$$

$$Z_3 = Z_2 + (.002 \times .9 \times H_D) \qquad \text{(c)}$$

$$Z = Z_3 + (.002 \times (24 - H_D)) \qquad \text{(d)}$$

where Z = total battery drain in amp-hours for one day

H_D = hours of darkness

R = actual lamp current, steady state, in amps

(a) is the lamp drain for 10 percent duty cycle and .4 sec flash
(b) is (a) plus the flasher drain during flash
(c) is (b) plus the flasher drain between flashes
(d) is (c) plus the daytime flasher drain

If the actual lamp current is known, this formula is very close in predicting the total load on the battery, and is at least as accurate as the coulometers. Because of this, we took the time to go through all of our lamps and selected for use only those that were .55 ± .01A or .77 ± .01A, and have been able to eliminate the 53 load coulometers and their associated problems from the test.

Results

One of the outputs of this test has been a computer program to design solar-powered systems for Coast Guard use. It has been verified by comparison with actual system operation. Figures 4.1-3, 4.1-4 and 4.1-5 show how it compares with three separate systems when actual insolation and best estimate of array efficiency are used. All other factors are as described previously. The original design prediction is also shown. It was based on estimates described at the beginning of Section 4.1 and even with insolation worse than predicted (Figure 4.1-1) was very conservative.

SYSTEM #25 BATTERY - 100 AH WISCO

LOAD - 12 V 0.77 A LAMP 10% DUTY CYCLE

ARRAY - SPECTROLAB NOMINAL 8.2 WATT

CURVE 1	CURVE 2	CURVE 3
ORIGINAL LOAD DESIGN	DATA DETERMINED	NEW LOAD DESIGN
24% ARRAY LOSSES	FROM SPECIFIC	10% ARRAY LOSSES
80% CHARGE EFFICIENCY	GRAVITY	≈100% CHARGE EFFICIENCY

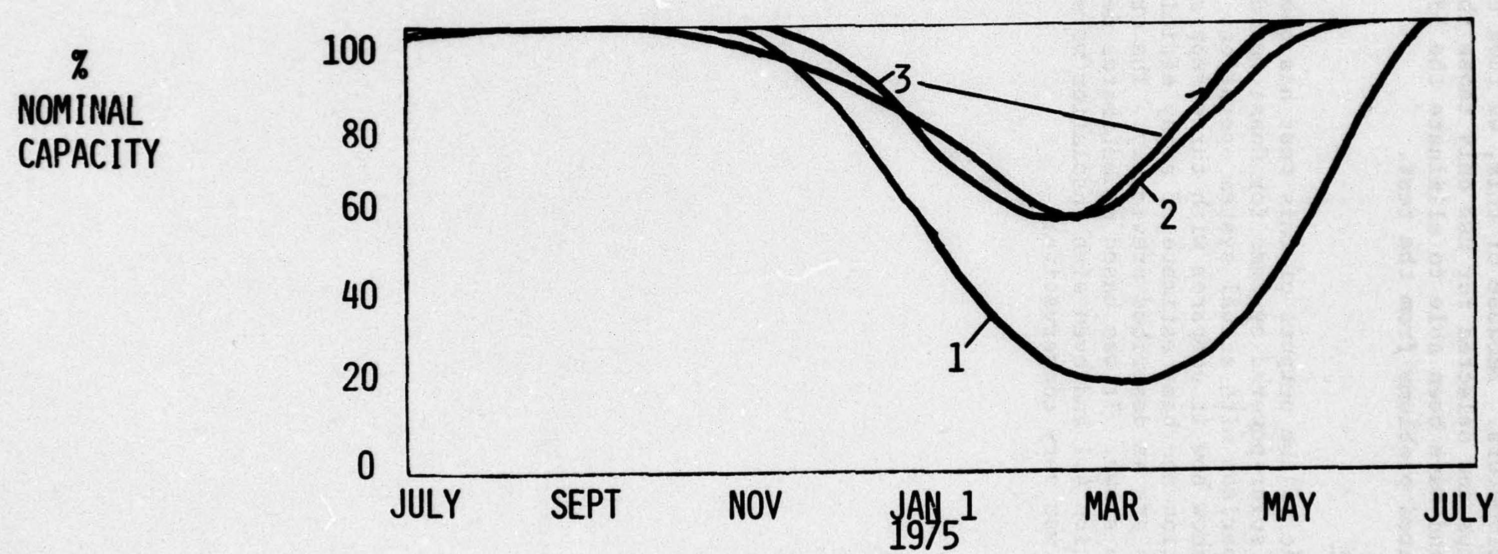


Figure 4.1-3

Comparison of Actual and Predicted System Performance

SYSTEM #43 BATTERY - 30 AH GATES

LOAD - 12 V 0.77 A LAMP 10% DUTY CYCLE

ARRAY - CENTRALAB NOMINAL 8.2 WATT

CURVE 1	CURVE 2	CURVE 3
ORIGINAL LOAD DESIGN	DATA DETERMINED	NEW LOAD DESIGN
24% ARRAY LOSSES	FROM VOLTAGE	5% ARRAY LOSSES
80% CHARGE EFFICIENCY	UNDER LOAD	≈100% CHARGE EFFICIENCY

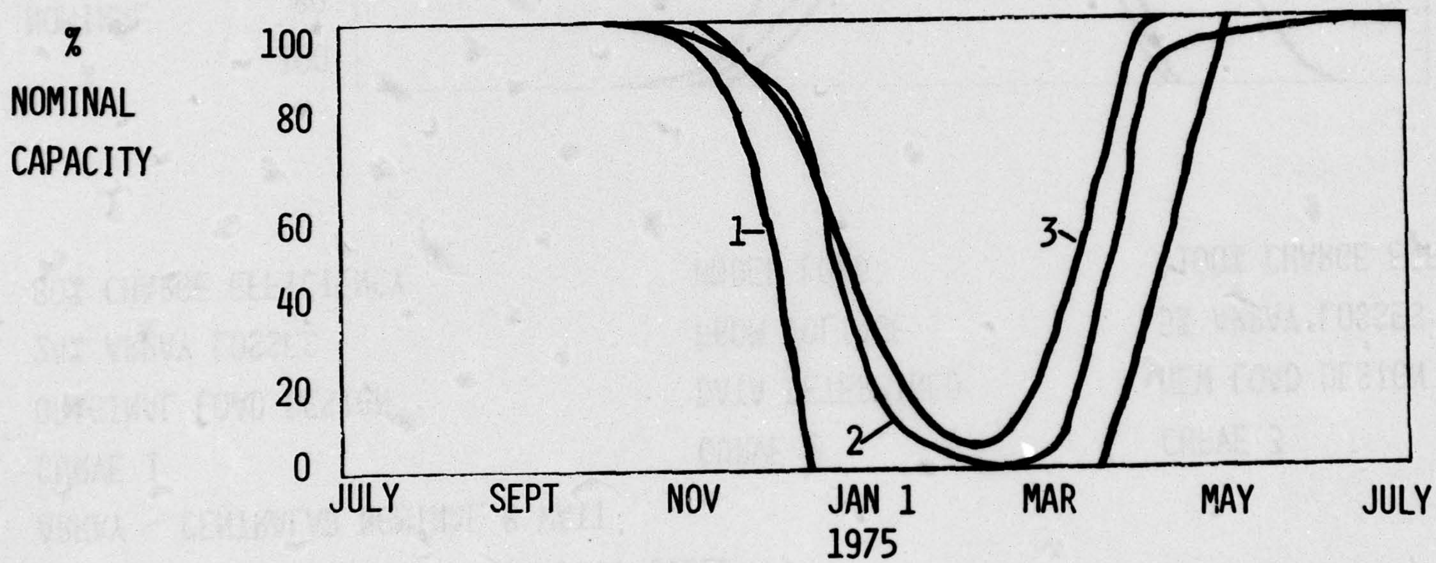


Figure 4.1-4
Comparison of Actual and Predicted System Performance

SYSTEM #52 BATTERY - 40 AH GLOBE

LOAD - 12 V 0.77 A LAMP 10% DUTY CYCLE

ARRAY - CENTRALAB NOMINAL 8 WATT

CURVE 1	CURVE 2	CURVE 3
ORIGINAL LOAD DESIGN	DATA DETERMINED	NEW LOAD DESIGN
24% ARRAY LOSSES	FROM VOLTAGE	5% ARRAY LOSSES
80% CHARGE EFFICIENCY	UNDER LOAD	≈100% CHARGE EFFICIENCY

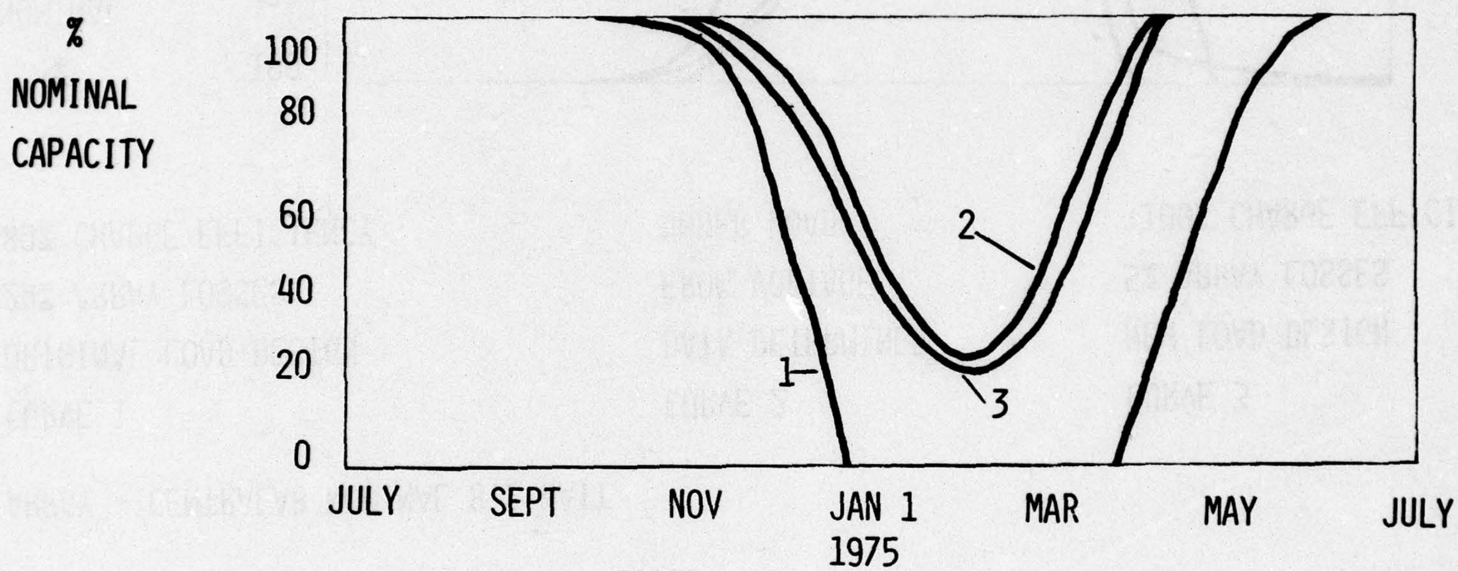


Figure 4.1-5

Comparison of Actual and Predicted System Performance

4.2 New Areas

By February 1976, 37 of the original 53 systems had failed or been removed from the test. Twenty-five of these were systems with Spectrolab arrays whose output was too erratic to give useful data, and six were systems with the 26Ah Wisco DA-2-1 batteries which the data indicated were not suited for this application. The other six failed because of corrosion, deliberate oversizing of the load or excessive charging without voltage regulation. The remaining 16 systems will continue to operate to build a long-term data base for future applications.

The first two years of operation have indicated several areas where information is incomplete or totally lacking and need further investigation.

Since zeners appear promising for use as voltage regulators, it is desirable to test them. By using some arrays from our "New Cell" program and arrays from systems whose operation, for various reasons, had been discontinued, it was possible to assemble 15 new systems using arrays with predictable outputs. Three of the arrays are a new type from Spectrolab while the rest are standard Centralab/OCLI.

We decided that a minimum of five "identical" systems of each type were needed and that we would test the effectiveness of 13.8V ± 5 percent zener diodes used as voltage regulators. The systems are designated A1-5, B1-5 and C1-5. All systems use two 6-volt, 100 Ah Mule liquid lead-acid batteries. Alternate cells 1, 3 and 5 are fitted with Mule's "Cell Ceal" caps while 2, 4 and 6 have standard caps. All systems have .55 ± .01 A lamps. This is a very small load for this size system and should produce much excess power in order to accent the differences in the systems. Group A systems will have no voltage regulation. This will be the control group. Group B will be regulated with 13.8V zener diodes They will also use the three new type Heliotek arrays which put out approximately 10 watts at 13.5 volts. Group C will be regulated with 13.1V (13.8 - 5%) zener diodes. Measurement of the amount of water used by each system will be the principal determining factor of the effectiveness of the items tested. Since there were not enough arrays to test 13.8V + 5 percent zener diodes, the control group will be looked at closely to see if it can be used to approximate the effect.

The expected system performance using 12-year average insolation for Newport, Rhode Island, is shown in Figure 4.2-1. This does not take into consideration the effects of a regulator.

The systems were initiated during August and September 1975, and performance will be described in future reports.

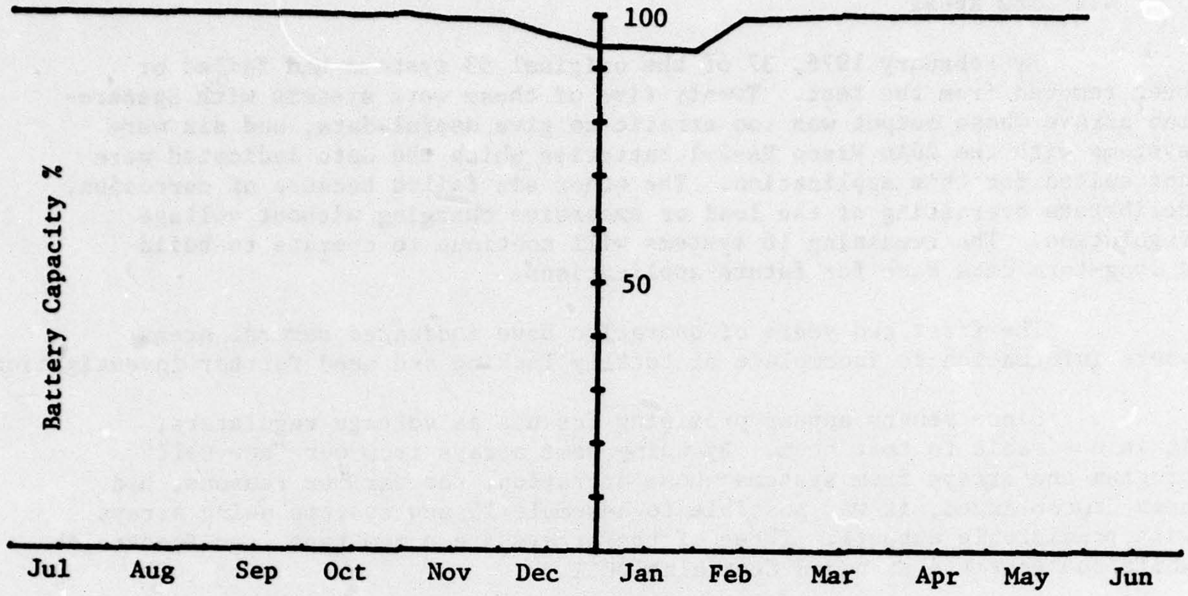


Figure 4.2-1. Predicted Performance of New Systems

There has also been interest in determining how much additional energy could be obtained by tilting the solar array, as opposed to horizontal operation. There are mathematical models that will predict the difference, but some persons have speculated that on cloudy, overcast days the insolation would be from diffuse radiation, and tilting the array would not increase the available energy. Since there are more of these overcast days in the winter, which is the time of interest for increasing available energy, the increase might be much less than predicted. We decided to get some actual data for the Groton area. Two identical Centralab modules were installed on the roof of a building at Avery Point and located at the water's edge. One of the modules is horizontal while the other is tilted at an angle of 56° from horizontal and on an azimuth of 180°T. The test was initiated in October 1975, and the data will be analyzed in future reports.

Additional data on batteries is required in several areas. We have started a test to determine the battery capacity that can be reached at a given charging voltage, which should identify the lower voltage limit of any regulating device that might be selected. We are also attempting to learn more about how batteries respond to different charge/discharge rates at different capacities. This is necessary for base data in a solar Design Integration Model that is being developed.

5.0 SUMMARY

It is difficult to give a concise summary on this work and more difficult yet to give conclusions since some of the work is still in progress. However, we will comment on the major items as they occur in the report.

Automatic Data Recording System - Such a system would not be used again. The prime drawback is manpower required in the maintenance and calibration of the "automatic" coulometers. These must be extremely accurate day after day if they are to correctly predict battery capacity after one or two years. A system which measured the solar array under full sun and the battery capacity on a regular basis would provide adequate data.

Insolation - The insolation received by an onshore aid or a nearby buoy will be virtually the same. There is a high probability that the existing weather (insolation) data can be used to correctly predict the operation of any aid to navigation in the waters of the continental United States.

Battery Boxes - All battery boxes should have an exterior color of white due to the rise in temperature which occurs inside boxes of other exterior colors.

Manual Coulometers - The manual coulometers of the mercury capillary tube type used in this project are not satisfactory for either field or laboratory work. They cannot be used to estimate battery capacity.

Spectrolab Arrays - The majority of the Spectrolab arrays failed during the first year of exposure. These failures were probably due to quality control vice the design of the array.

Centralab Arrays - Only a few failures of Centralab arrays have occurred during the first two years. The failures were caused by the corrosion of terminals which were not sufficiently sealed.

Voltage Regulation - At this stage of our investigation, voltage regulation is recommended for operational systems. There is no doubt that in some systems voltage regulation will extend battery life.

26 Ah Wisco Battery - This battery proved unsatisfactory due to its small size. The small physical size made measuring the specific gravity or regulating the electrolyte very difficult. The small capacity resulted in excess water loss during summertime overcharge periods.

100 Ah Wisco Battery - This battery has proved highly satisfactory. If a liquid electrolyte lead-acid battery is provided with spill-proof caps and proper voltage regulation, it will be the most cost effective choice for the energy storage system.

Globe Battery - This battery had the highest initial rejection rate for failure of new batteries to deliver rated output. In operation they have failed due to corrosion of the terminals and loss of capacity. However, it remains a candidate for our application.

Gates Battery - This battery had a high initial rejection rate. Since the basic cell is a 2.1 volt, 5 Ah unit, any battery consists of many series-parallel strings. This in turn leads to failures.

System Design - A simple computer program is used for the design of systems. The program uses average monthly insolation, a straight panel efficiency, a complex charge efficiency and a load based on average hours of darkness. The design has a good match to actual systems in operation.

APPENDIX A

INTEGRATED INSTRUMENTATION SYSTEM

A block diagram of the functions performed by the instrumentation system is shown below. The sensors, collection, conversion and recording blocks make the connection for information to flow from the experiment to data processing. The timing and control blocks coordinate the functions themselves.

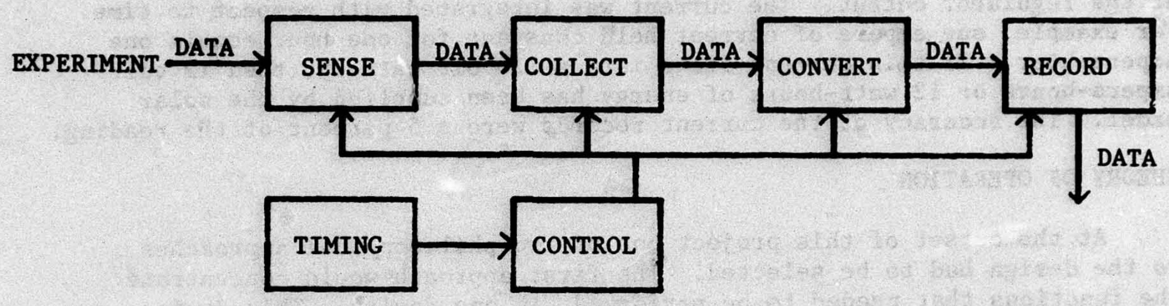


FIGURE A-1 - INSTRUMENTATION FUNCTIONS

INSTRUMENTATION REQUIREMENTS

The instrumentation system needed to be designed for continuous operation for a period no less than three years. During the operation of the equipment, it would be necessary to modify various portions of the experiment and perform routine maintenance, repair and calibration of sensors and other system equipment without affecting the collection of routine data (the specific area of concern being all current integrating sensors). Due to the 24 hour a day, 7 day a week continuous operation, human interaction had to be minimized.

In each of fifty-three solar energy systems the automatic instrumentation was required to monitor:

1. Electrical current flow out of the solar array.
2. Electrical current flow to the battery.
3. Electrical current flow from the battery to the power load.
4. The voltage of the battery under both charge and loaded conditions.

Two "standard" solar cells were used to monitor insolation and the electrical current produced by each of these was recorded.

Because the voltage of each system's battery changed very slowly over the charge/discharge cycle, two voltage readings a day were considered sufficient to give meaningful information; one reading taken at the battery's peak charge and the other reading during fully loaded conditions. Each voltage reading was taken with a resolution of .01 volt.

The electrical current produced by the solar arrays was identical to the electrical current flowing into the battery in every system except those that used regulators. The electrical currents of the non-regulated solar energy systems were monitored at the solar array output and the load input. In the regulated systems, the electrical current was also monitored at the regulator output. The current was integrated with respect to time. For example, one ampere of current held constant for one hour equals one ampere-hour. If this current flows into a 12-volt battery, then 12 volt-ampere-hours or 12 watt-hours of energy has been supplied by the solar panel. The accuracy of the current records were ± 5 percent of the reading.

THEORY OF OPERATION

At the outset of this project one of two philosophical approaches to the design had to be selected. The first approach would concentrate the functions that needed to be performed, in one device. This device would monitor all the events on a sampled basis. This sampled data could then be compiled and the necessary output produced. The only device, within reason, capable of performing all the required work is a minicomputer. Prior experience with minicomputer systems indicated that this configuration would have difficulty meeting the 24 hour a day, 7 day a week endurance required for this experiment. The other unattractive feature of relying on one device to perform all functions was the "hard" or catastrophic failure nature of the final instrumentation system. The system would be either working or not working with very little buffer between. However, the second approach, a distributed instrumentation system, has a "soft" or recoverable failure nature. Component reliability in both approaches were equivalent, but desiring to lose as little data as possible in the case of a single failure, the choice was made to spread the work load using a distributed system which incorporated individual integrating current sensors. A distributed system would also allow greater flexibility in performing repairs and calibrations without affecting the operation of the entire instrumentation system.

In this distributed instrumentation system, voltage and integrated current values were monitored and recorded. The task of measuring voltage values was straightforward. Each voltage measurement was taken using a single digital voltmeter and an analog signal multiplexer that connected the voltmeter to selected batteries. The current monitoring was a more difficult problem.

Several methods of measuring electrical current exist. Some devices measure the magnetic field produced by the movement of electrons in a conductor. Other devices measure the voltage drop across a known resistance. All the circuits considered for this project operated on the voltage drop principle.

The voltage drop was provided by a 0.100 ohm current shunt placed in the desired electrical current paths. The type of sensor that was selected, integrated the current (voltage) with respect to time (thus providing ampere-hours).

Every exclusively electronic method of measuring the current that was considered, converted the input current (voltage) to a pulse signal. Each pulse would equate to a small quantity of ampere-hours. The number of pulses would be totaled over an interval of time (i.e. hours of daylight) and recorded at the end of the time period. Unfortunately, because of the quantity of sensors needed for the experiment (126), these devices could not be purchased commercially for what we considered a reasonable price.

A sensor was located that promised an accuracy of 5 percent for each reading at a price of less than $100 each. The sensor combines both chemical and electrical components. A passive chemical component, called a coulometer, performs the current integration. The actual chemical process is a coulometric electroplating process utilizing liquid mercury in a narrow tube, separated by an electrolytic solution. The mercury is plated from one side of the electrolyte gap to the other in proportion to the current through the 0.100 Ω shunt and the electrolyte gap moves down the tube. The plating process is completely reversible. The coulometer continues to integrate even if the power is removed from the sensor's electronics. In this project the term coulometer is used to mean the current integrating sensor, even though strictly speaking it is only the integrator.

The current integral recorded by a coulometer is "read" by an electronic circuit in each sensor. The electronic circuit converts the existing value for the integrated current, based on the position of the electrolyte gap, into an oscillator frequency. The frequency of this oscillator (f) is related to the current integral (I) by the formula,

$$I = A + Bf + Cf^2$$

where the values for A, B and C are calculated by a computerized curve fit program using calibration data for input.

The coulometer needs to be reset daily. Due to the nature of the chemical process involved, the reset cycle takes about two hours. When the device is "reset," the oscillator does not always indicate the same ampere-hour reading. For accurate values the coulometer frequency must be recorded prior to a monitoring period as well as at the end. The value used for ampere-hours observed during the period is the difference of the two readings.

The oscillator outputs of the coulometers were connected to a single frequency meter through an analog signal multiplexer identical to that used for the voltage signals. In order to provide a stable environment for these sensors, they were housed inside an air conditioned enclosure.

INSTRUMENTATION HARDWARE

The design and construction of the hardware making up the actual instrumentation system was dictated by the requirements placed on the system by the experiment and the nature of the sensors selected. As was shown in Figure A-1, six major functions must be performed by the instrumentation hardware; (1) monitoring, (2) collecting, (3) converting, (4) recording, (5) timing, and (6) controlling. Figure A-2 expands Figure A-1 to call out the actual hardware devices used in constructing the final instrumentation system.

The data enters the system from the experiment in the form of electrical currents or voltages (the upper left of the diagram shows the analog current data being converted into voltages at the 126 current shunts). Directly connected to each current shunt is a coulometer. The electrical current information is stored in each of 126 coulometers. The analog signal from each coulometer oscillator and the voltage from each battery is connected to an individual terminal on the 70GP10 scanner system. The analog voltage and coulometer signals are subsequently connected to either the voltmeter or frequency counter inputs. The analog voltage data is converted into digital format by the digital voltmeter, while the analog frequency is converted into digital format by the frequency counter. The digital data signals and digital information signals from the Julian clock and scanner system enter a digital data multiplexer which routes the correct information to the paper tape punch for recording.

The flow of the data from the experiment to the paper tape media is coordinated by the controller logic and timing equipment. This equipment organizes the operation of the data collection process. The following event table (Table A-1) describes the operations performed by each element in the instrumentation system during the recording of a particular data record. Note in the description that timing control is passed from device to device during the course of recording one data record (data records are described later). In this manner each device making up the instrumentation system is allowed to complete its function before control is passed to the next device. This method of control is often referred to as "handshake control" and allows assorted equipment of various designs to be interconnected without critical attention to the timing requirements of any one piece of equipment. The controller logic does not have "absolute" control over all the equipment making up the instrumentation system, but does have some override capability in the event that the primary handshake control path is interrupted and the instrumentation systems become "hung up."

Table A-1
SEQUENTIAL ORDER OF INSTRUMENTATION EVENTS

Event No.	Event
1	The SCANNER SYSTEM advances to the next sequential data channel.
2	After the scanner circuits have stabilized on the next channel, this fact is indicated by enabling the RECORD CMD 1 line to the CONTROLLER LOGIC.

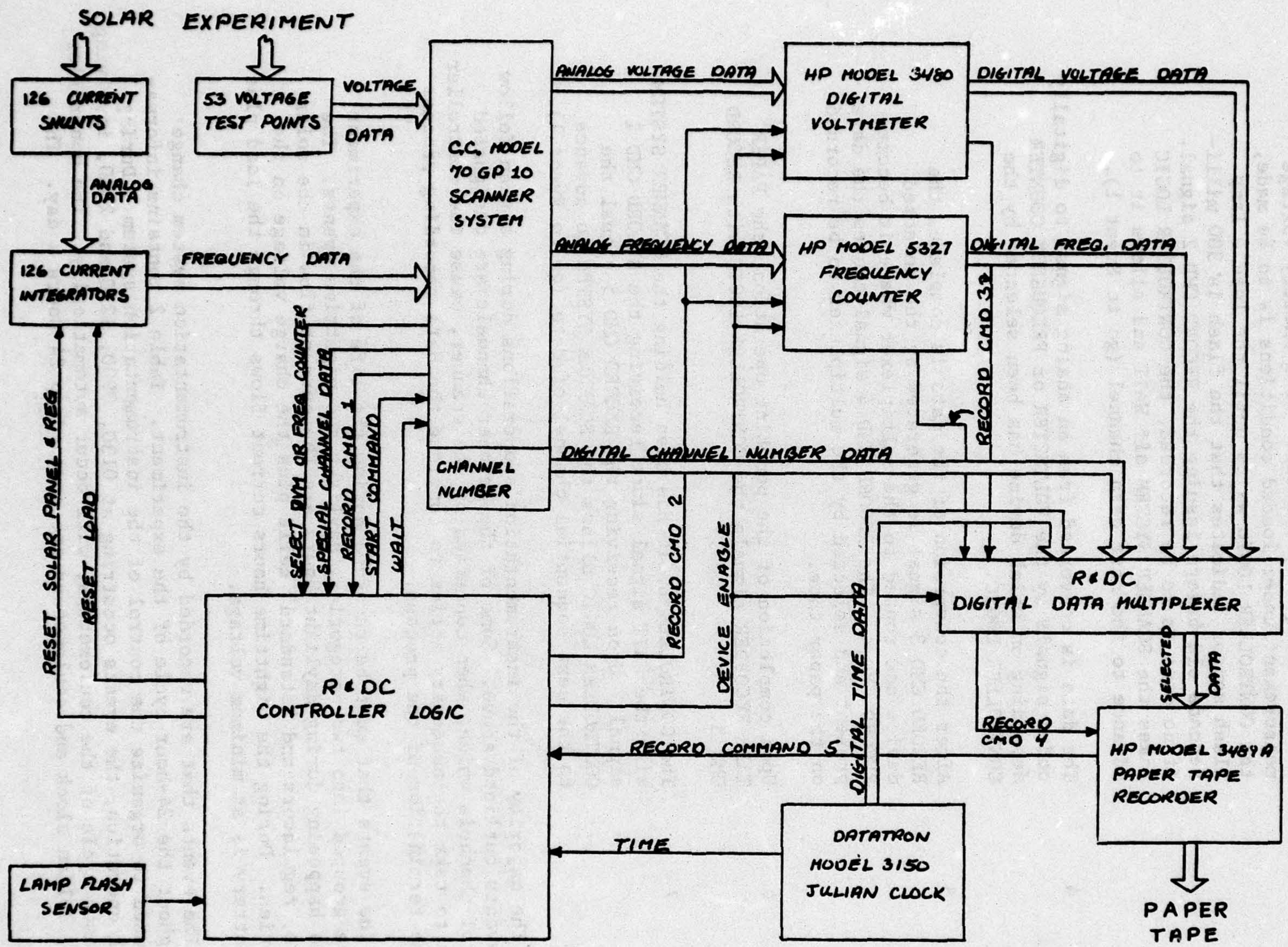


FIGURE A-2. DETAILED INSTRUMENTATION FUNCTIONS.

3 The CONTROLLER LOGIC controls the next event. If a frequency measurement or no-load voltage conversion is to be made, a RECORD CMD 2 signal is given to the voltmeter or frequency counter. If a battery voltage measurement under loaded conditions is to be made, the CONTROLLER LOGIC waits until the load's lamp flash sensor indicates that the flash is 300 milliseconds old before issuing the RECORD CMD 2 signal. If no data is to be recorded, the CONTROLLER LOGIC takes the SCANNER SYSTEM off WAIT and allows it to advance to the next data channel (go to Event 1).

4 The data is converted from an analog signal to digitally coded signals by the VOLTMETER or FREQUENCY COUNTER depending on which device has been selected by the CONTROLLER LOGIC.

5 After the conversion of the data is complete, the RECORD CMD 3 signal is generated by the selected device and routed to the multiplexer where it becomes RECORD CMD 4. The RECORD CMD 4 signal causes the data present and selected by the multiplexer to be recorded on the paper tape.

6 Upon completion of the punching operation, the PAPER TAPE RECORDER signals the CONTROLLER LOGIC with RECORD CMD 5.

7 The CONTROLLER LOGIC has been holding the SCANNER SYSTEM with the WAIT signal since receiving the RECORD CMD 1 signal. Upon receiving the RECORD CMD 5 signal the CONTROLLER LOGIC allows the SCANNER SYSTEM to advance to the next sequential channel of data (go to Event 1).

The majority of the instrumentation's operations during a scan follow the events outlined above. Some of the scanner channels are designated control channels which, when connected by the scanner, cause the controller logic to take the necessary action to continue the data recording process or the termination of the process.

The events that must be recorded during the life of the experiment can be grouped into two categories, daylight and nighttime events. The events happening during daylight hours are the current flow in the solar arrays, regulators and "standard" cells plus the charge voltage on the batteries. During the nighttime hours current flows through the load plus the battery is at minimum voltage.

The events that are recorded by the instrumentation system change throughout the 24-hour cycle of the experiment. Table 2 contains information used to organize the control of the instrumentation system. During normal operation, the events occurring at 0130, 0900, 1200 and 2030, involving the reset cycle of the coulometers, will occur automatically. The controller logic, Julian clock and coulometers are powered up 24 hours a day. The

remainder of the instrumentation is normally off. It is powered up automatically, 30 minutes prior to recording data. In this report, a data recording session is referred to as a scan. Under normal conditions, each type of scan is selected to occur once each 24-hour period, but the time that they occur can be changed as the hours of daylight change during the year.

Table A-2

MAJOR INSTRUMENTATION EVENTS SCHEDULE

Time	Event
0130	Discontinue the reset cycle of all solar array and voltage regulator coulometers.
0200	A data scan is performed during which the initial ampere-hour (frequency) value for each solar array and regulator coulometer is recorded. The battery voltage under load for each solar energy system is also recorded. Alternate times for this scan are 0000, 0300 and 0400.
0600	During this data scan, the final ampere-hour (frequency) value for each load coulometer is recorded. Alternate times for this scan are 0500 and 0800.
0900	Start the reset cycle for all the load coulometers.
1200	Discontinue the reset cycle for the load coulometers.
1400	A data scan is performed during which the initial ampere-hour (frequency) value for each load coulometer is recorded. The battery voltage at peak charge for each solar energy system is also recorded. Alternate times for this scan are 1300 and 1500.
2000	A data scan is performed during which the final ampere-hour (frequency) value for each solar array and regulator coulometer is recorded. Alternate time for this scan is 1800.
2030	Start the reset cycle of all solar array and voltage regulator coulometers.

The output of the instrumentation system is punched paper tape. This media was selected because it was the most universally acceptable by the computational equipment at the R&D Center. The data of each event is recorded a record at a time on the punched paper tape serially in standard USASCII code.

In the original configuration for the experiment there were 181 different data records that could be potentially recorded during a given data scan. There were 53 solar arrays, 18 regulators, 53 loads and two

"standard" cell coulometers. Fifty-three battery voltages needed to be recorded and the beginning and end of each data scan was identified with a date time group that was used to identify the type of scan occurring and the date of the occurrence. As can be seen by studying Table A-2, no single data scan recorded 181 data records. Scan 0200 records 128 data records. Scan 0600 records 55 data records. Scan 1400 records 108 data records, and scan 2000 records 75 data records.

If the recorded tape is listed by using a Teletype, a series of records is printed as shown in Table A-3. Each record contains two numbers separated by a ± sign. Some records contain a third number, "2," that can be ignored. The first record of each data scan contains the date-time group (three digit Julian day, two digit hour and the tens of minutes value) and a second meaningless number that is normally zero. All the records containing data have three zeros for the first three characters and channel numbers from 002 to 192 for the following three characters. The second number of each data record is the data itself. Each channel number is associated with one and only one possible sensor. Therefore, if the channel number is known, the sensor is known. The following table (Table A-4) lists the association of channel numbers with particular solar energy systems.

The instrumentation that has been described has been in operation for two years. During this period, problems with the equipment have randomly occurred, most of which have been corrected quickly with little loss of data. Only the coulometers have been a continuing problem area. The mean time between failures has been about six months. Consequently the current integrating sensors are continually being repaired, calibrated and installed. Fortunately the manufacturer of the device has been very cooperative in assisting the R&D Center with the repairs and necessary replacements. The overall performance of the instrumentation system could be improved if a more accurate and reliable current integrating sensor could be obtained at a reasonable price (about $100 each).

TABLE A-3
ANNOTATED LISTING OF TYPICAL PAPER TAPE

182150+00001E-2	START OF 1500 SCAN (DAY IS 182D OF YEAR)
000079-6063E-	INITIAL FREQ. SOLAR SYSTEM 1 LOAD COUL. = 6063 HZ.
000080-6072E-	INITIAL FREQ. SOLAR SYSTEM 2 LOAD COUL. = 6072 HZ.
000081-5983E-	ETC.
000082-6209E-	.
000083-6087E-	.
.	.
.	.
000130-6036E-	
000131-6139E-	INITIAL FREQ. SOLAR SYSTEM 53 LOAD COUL. = 6139 HZ.
000140+01475E-2	NO LOAD VOLT. BATTERY OF SOLAR SYSTEM 1 = 14.75 V.
000141+01251E-2	NO LOAD VOLT. BATTERY OF SOLAR SYSTEM 2 = 12.51 V.
000142+01441E-2	ETC.
.	.
.	.
00019+01610E-2	.
000192+01437E-2	NO LOAD VOLT. BATTERY OF SOLAR SYSTEM 53 = 14.37 V.
182151+00001E-2	END OF 1500 SCAN
182220+00001E-2	START OF 2200 SCAN
000002-4613E-	FINAL FREQ. OF SOLAR SYSTEM 1 ARRAY COUL. = 4613 HZ.
000003-5687E-	FINAL FREQ. OF SOLAR SYSTEM 2 ARRAY COUL. = 5687 HZ.

TABLE A-4
ASSOCIATION - CHANNEL NUMBER AND SENSORS

CHANNEL NUMBER	SENSOR
002	Solar array coulometer for solar energy system 1
003	Solar array coulometer for solar energy system 2
.	
.	(Sequential channel numbers associate with sequential systems)
.	
054	Solar array coulometer for solar energy system 53
055	Regulator coulometer for solar energy system 1
.	
.	
.	
072	Regulator coulometer for solar energy system 18
073	Standard cell 1 coulometer
074	Standard cell 2 coulometer
079	Lamp load coulometer for solar energy system 1
080	Lamp load coulometer for solar energy system 2
.	
.	
.	
131	Lamp load coulometer for solar energy system 53
140	Battery voltage of solar energy system 1
141	Battery voltage of solar energy system 2
.	
.	
.	
192	Battery voltage of solar energy system 53

APPENDIX B

ENCLOSURE (1) to COMDTINST 10500.32
3 Mar 1972

RATED BATTERY DISCHARGE TIME
Method of Calculation

$$\frac{\text{Ampere-hours}}{\text{day}} = \text{Avg. Lamp Current} \times \text{Duty Cycle} \times \text{Hours Per Day} + \text{Flasher Dissipation}$$

Average Lamp Current, during flash corrected for cold filament surge:

Nominal Lamp Rating, Amps	Average Current in amps for Various flash duration time in seconds					
	.3 sec.	.4 sec.	.5 sec.	1.0 sec.	2.0 sec.	3.0 sec.
.25	.278	.271	.268	.258	.254	.252
.55	.639	.621	.605	.578	.564	.559
.77	.916	.894	.870	.816	.793	.785
1.15	1.42	1.38	1.33	1.24	1.20	1.18
2.03	2.76	2.62	2.50	2.23	2.13	2.10
3.05		4.15	3.91	3.42	3.24	3.17

Duty Cycle, and flash duration time

Flash Characteristic	Duty Cycle	Flash Period
FL4(.4)	.10	0.4 sec.
GPFL5(2X.4)	.16	0.4
FL6(1.0)	.167	1.0
IQKFL(6X.3)	.18	0.3
FL2.5	.20	0.5
FL4(1.0)	.25	1.0
MO(A)(.4,2.0)	.30	0.4, 2.0
QKFL1.0(0.3)	.30	0.3
GPFL6(2X1.0)	.33	1.0
EI6(3.0)	.50	3.0
OCC4(3.0)	.75	3.0

Flasher Dissipation in ampere-hours (Maximum allowable by EOE Purchase Description No. 181B):

Night: $$\frac{[10 \text{ ma} + 20 \times (\text{duty cycle}) \text{ ma}] \times \text{night time hours}}{1000}$$

Day: $$\frac{6 \text{ ma}}{1000} \times \text{Daylight hours at } 70°\text{F}$$

$$\frac{25 \text{ ma}}{1000} \times \text{Daylight hours at } 125°\text{F}$$

Total Daily Flasher Dissipation = total of night and day dissipation

$$\text{Rated Battery Discharge Time} = \frac{\text{Ampere-hour capacity of Battery}}{\text{Ampere-hours/day}}$$

☆ U. S. GOVERNMENT PRINTING OFFICE: 1976--700-262--30